WATER RESOURCES OF BORREGO VALLEY

SAN DIEGO COUNTY, CALIFORNIA

A Thesis

Presented to the

Faculty of

San Diego State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in

Geological Sciences

---

by

Steven Paul Netto

Fall 2001

THE UNDERSIGNED FACULTY COMMITTEE APPROVES

THE THESIS OF STEVEN PAUL NETTO:

David Huntley — 12/6/01

David Huntley, Chair
Department of Geological Sciences

Date

Kathryn W. Thorbjarnarson
Department of Geological Sciences

Christina Tague
Department of Geography

SAN DIEGO STATE UNIVERSITY

Fall 2001

ACKNOWLEDGMENTS

First and foremost I would like to thank my wife Patti. She has sacrificed much over the years while supporting me in so many ways that I cannot find words adequate to express the gratitude that I feel. She has always been there for me and has carried more than her share as I have been occupied with coursework and this thesis effort, while at many times postponing or altogether foregoing her own interests.

To my parents, Arnold and Velma Netto, I owe so many thanks. They have frequently expressed their interest, support and encouragement, and from them I have experienced the deepest kindness and generosity. Inspiring words from my father have stuck with me while finishing this thesis, he reminded me that it would take a lot of tenacity, not just know how, to finally get it done. And to my mother, Joan Fordyce, I also owe a debt of gratitude, for always being there with her love, support and enthusiasm.

I am very fortunate to have had the opportunity to work with Dr. David Huntley on this project. It has been an enlightening experience for me and I have learned much from him that I will carry with me throughout the rest of my career. His patient guidance and his willingness to work with me at almost anytime, at his office, over the phone, or even at his own home, have been greatly appreciated. I would also like to thank my committee members, Dr. Kathy Thorbjarnarson and Dr. Christina Tague, for their time and helpful comments during review of this thesis.

I would also like to express thanks to Hargis + Associates for all the support they have given me, and all the contributions of company time that they have allowed for the graphics group to work with me on many of the figures in this thesis. Special thanks goes to Mike Palmer and to Chris Ross, for always keeping me motivated and allowing me to keep such a flexible work schedule throughout the past several months. Special thanks also goes to the graphics group, especially Alex Easton and Steve Stewart, for providing their expertise in drafting and valued suggestions with graphics, and to Anita Akacki, for her time spent formatting, reviewing the text, and copying.

This thesis would not have been possible without the assistance and cooperation of John Peterson at the County of San Diego, Department of Planning and Land Use, and the many people of Borrego Valley who have contributed so much to this work. Sam and Scott Fortiner and Stan Bauer have allowed access to wells for testing and to their citrus groves for the collection of soil core samples. Andy Gorton at the De Anza Country Club also allowed access to the golf course for collection of soil core samples. Lin Burzell, with the Borrego Water District, coordinated access to wells that were tested with the assistance of Victor Lugo. Bob Zinser contributed a wealth of information regarding wells, land use and groundwater use in the valley. Jack Laughlin, who was very much concerned with water resource issues in Borrego Valley, was a strong proponent for the forming of a cooperative groundwater management group to evaluate the future water supply for Borrego Valley. Jack Laughlin also provided valuable information for this study regarding groundwater use in the valley.

I am lucky to have many friends to thank for their encouragement, help with fieldwork, and shared enthusiasm in my completing this thesis. Steve Blackwell, John Hank, Cathy Martin, Dave Renfrew and John Tyner helped with aquifer testing, soil core sampling, stream gauging, laboratory analysis, and/or drafting. Very special thanks goes to Tom Henderson, who has been both a partner in this study, and a valued friend.

TABLE OF CONTENTS

PAGE

CHAPTER PAGE

CHAPTER PAGE

LIST OF TABLES

LIST OF FIGURES

FIGURE (continued) PAGE

FIGURE (continued) PAGE

PLATE

CHAPTER I

INTRODUCTION

The groundwater aquifer system underlying Borrego Valley currently represents the sole source of potable water to Borrego Springs and the surrounding community for municipal, agricultural and recreational demands. Groundwater has been extracted from the Borrego Valley aquifer since the early part of the 20th century. Beginning in the late 1940s, and occurring throughout much of the development in Borrego Valley, groundwater extraction has exceeded natural groundwater recharge, resulting in an apparent overdraft condition. Overdraft of the aquifer has resulted in a decline of groundwater levels in the majority of monitored wells and depletion of the volume of groundwater in storage within the aquifer system.

Purpose

The primary purpose of this study was to develop a conceptual model of the groundwater aquifer that supplies water to Borrego Valley, sufficient for the construction of a numerical groundwater flow model. Specific objectives of this study were to (1) define the occurrence and geometry of geologic materials comprising the aquifer system, (2) characterize the hydraulic properties of the aquifer materials, (3) evaluate recharge to, and discharge from, the groundwater basin, and (4) quantify the net loss in groundwater storage within the Borrego Valley Aquifer.

Location and General Features of Borrego Valley

Borrego Valley is located in the northeastern portion of San Diego County, California, approximately 85 miles northeast of the city of San Diego (Figure 1). This area of San Diego County is within the Colorado Desert geomorphic province of California and lies along the margin of the desert region to the east, with a more humid region in the mountains of the Southern California Batholith to the west. Borrego Valley is bounded on the north and northeast by Coyote Mountain, on the west and southwest by the San Ysidro Mountains and Pinyon Ridge, and on the south by the Vallecitos Mountains (Figure 2). The east side of Borrego Valley is bounded by the Coyote Creek fault, with the Borrego Badlands beyond,

Figure 1. Regional Location Map.

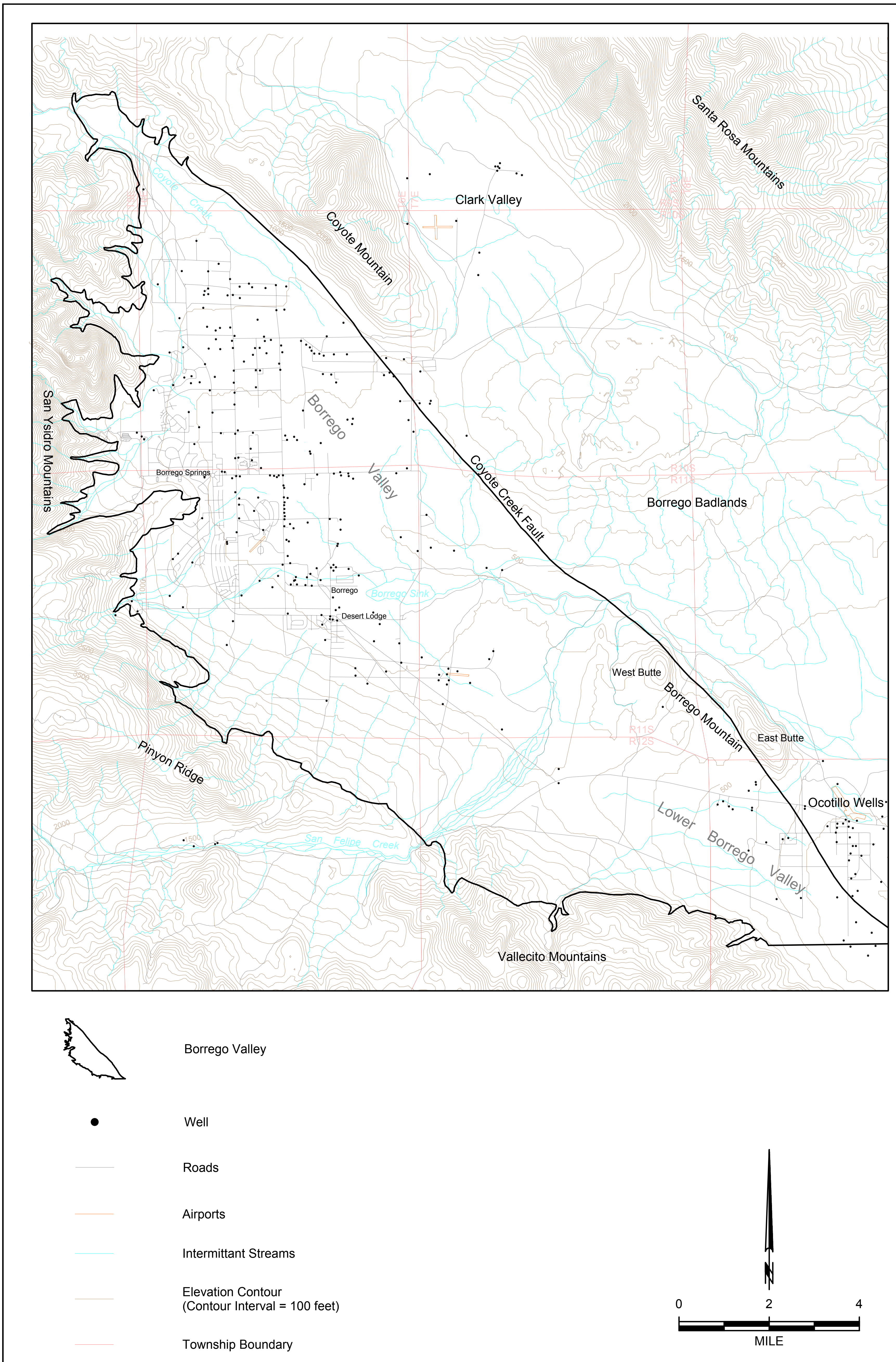


Figure 2. Borrego Valley.

and Borrego Mountain. To the southeast, San Felipe Creek forms the boundary between Borrego Valley and Lower Borrego Valley (Figures 2 and 3).

Topography

The 110 square mile valley floor ranges in elevation from 1,200 feet at the northern end of the valley, in the vicinity of Ocotillo Flat near Coyote Canyon, to approximately 460 feet in the vicinity of Borrego Sink. The elevation of the valley floor generally ranges from about 800 to 1,000 feet around the margins of the basin, and declines towards the center of the valley to Borrego Sink (Figure 2). The surrounding mountains are characterized by steep slopes with elevations ranging from 800 to 1,000 feet, where the mountain slopes reach the valley floor, to mountain peaks ranging in elevation from approximately 1,700 feet at Yaqui Ridge (southeast extension of Pinyon Ridge) to over 6,500 feet at Hot Springs Mountain (in the San Ysidro Mountains) (Figure 3). The Borrego watershed extends far to the north of Borrego Valley, into the southern portions of Riverside County, with its highest reaches extending to over 8,700 feet at Toro Peak in the Santa Rosa Mountains (Figure 3).

Climate

Borrego Valley has an arid climate with average annual precipitation on the valley floor ranging from 3 to 6 inches. The mountains to the west of the valley have a more humid climate with average annual precipitation ranging to more than 16 inches. Most of the precipitation occurs during the winter months, between November and April. However, summer thunderstorms do occur, with summer precipitation typically peaking in August with an average monthly precipitation of about 0.5-inch throughout much of the watershed (Figure 4). The climate in Borrego Valley is characterized by hot summers and cool winters. Average high temperatures typically exceed 105°F in July and low temperatures are typically below 40°F in December and January (Figure 5). Potential evapotranspiration is estimated to exceed 70 inches in the vicinity of Borrego Valley annually, ranging up to about 10 inches per month during the summer months (discussed in Chapter 4) (Figure 6).

Vegetation

Native vegetation in Borrego Valley consists of desert scrub that is characteristically found in the western margin of the Colorado Desert. Common trees and shrubs include ocotillo, creosote bush, ambrosia, mesquite and several species of cactus. Exotic phreatophytes, predominantly tamarisk, have invaded many of the washes and much of the

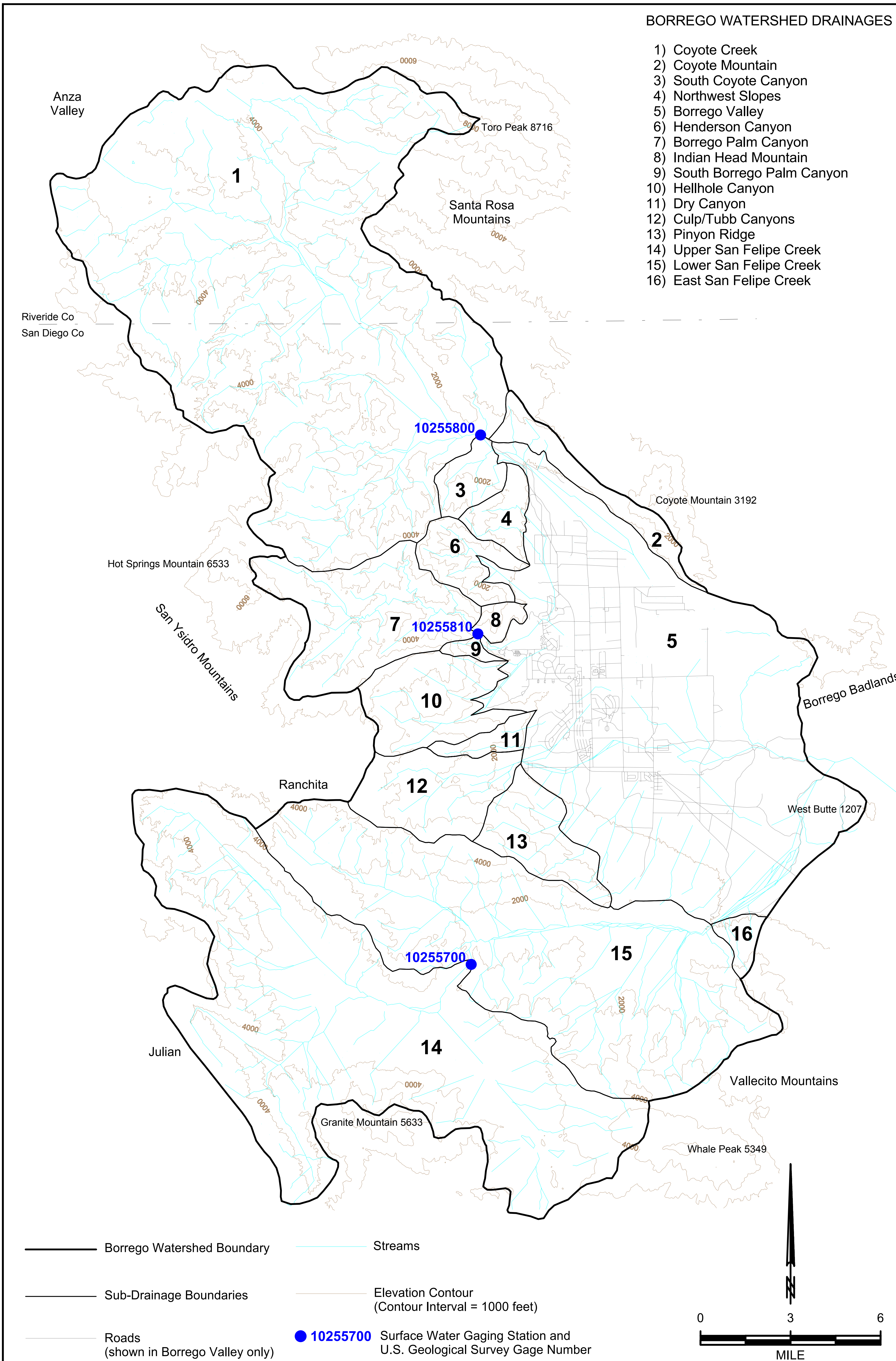
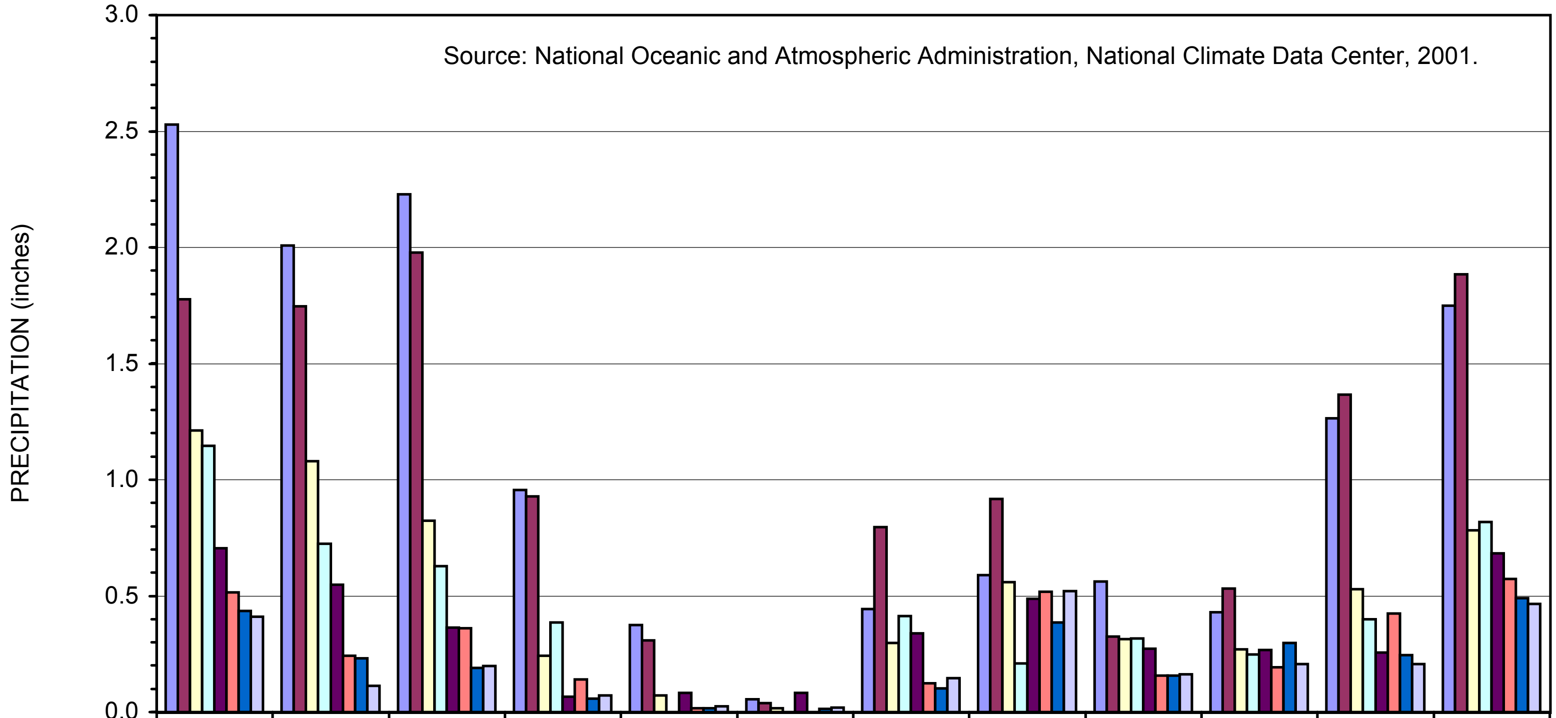
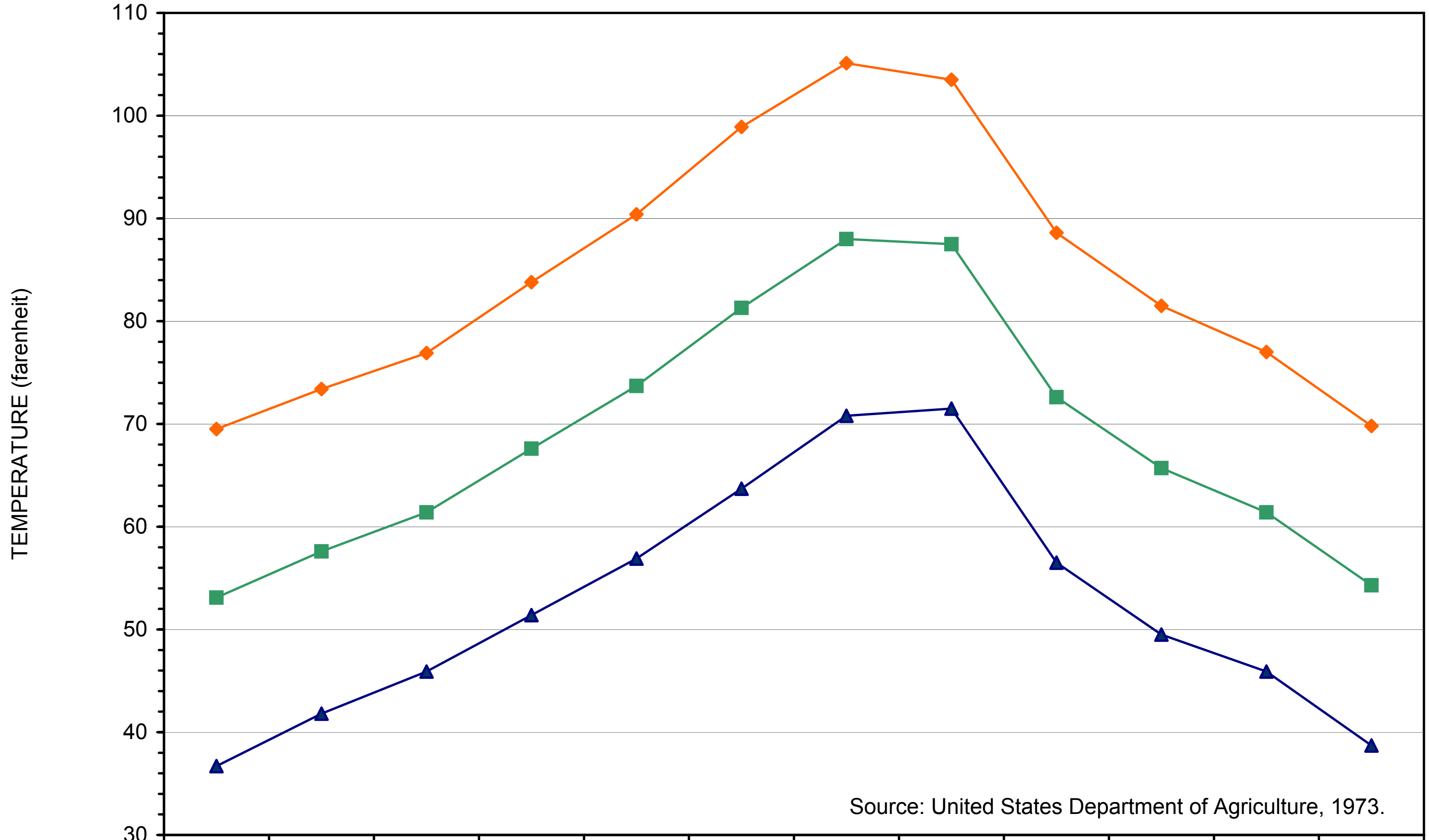


Figure 3. Borrego Watershed.



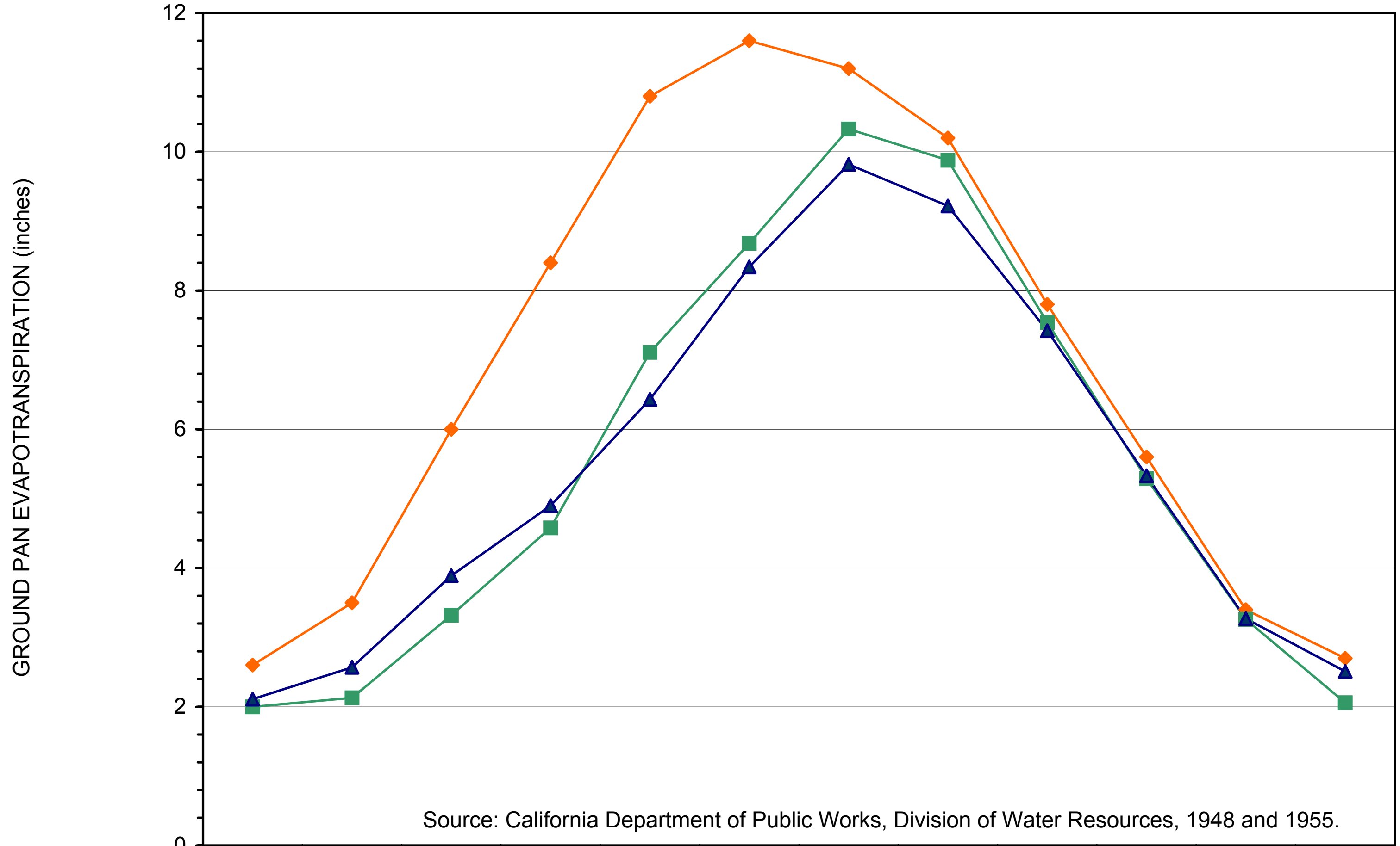
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Anza	2.53	2.01	2.23	0.95	0.37	0.06	0.44	0.59	0.56	0.43	1.26	1.75
Ranchita	1.78	1.75	1.98	0.93	0.31	0.04	0.80	0.92	0.33	0.53	1.37	1.89
Borrego Park	1.21	1.08	0.82	0.24	0.07	0.02	0.30	0.56	0.31	0.27	0.53	0.78
Coyote Canyon	1.15	0.72	0.63	0.39	0.00	0.00	0.41	0.21	0.32	0.25	0.40	0.82
Ocotillo 2	0.71	0.55	0.36	0.07	0.08	0.08	0.34	0.49	0.27	0.27	0.26	0.68
Borrego Springs	0.52	0.24	0.36	0.14	0.02	0.00	0.12	0.52	0.16	0.19	0.42	0.57
Ocotillo Wells	0.44	0.23	0.19	0.06	0.02	0.01	0.10	0.38	0.16	0.30	0.25	0.49
Coyote Wells	0.41	0.11	0.20	0.07	0.03	0.02	0.15	0.52	0.16	0.21	0.21	0.47

Figure 4. Monthly Mean Precipitation, Borrego Valley and Vicinity, California.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Mean High	69.5	73.4	76.9	83.8	90.4	98.9	105.1	103.5	88.6	81.5	77.0	69.8
Monthly Mean	53.1	57.6	61.4	67.6	73.7	81.3	88.0	87.5	72.6	65.7	61.4	54.3
Mean Low	36.7	41.8	45.9	51.4	56.9	63.7	70.8	71.5	56.5	49.5	45.9	38.7

Figure 5. Monthly Mean Temperature, Borrego Springs, California.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
US Date Garden, Indio	2.60	3.50	6.00	8.40	10.80	11.60	11.20	10.20	7.80	5.60	3.40	2.70
Henshaw Reservoir	2.00	2.13	3.32	4.58	7.11	8.68	10.33	9.88	7.54	5.29	3.26	2.06
Morena Reservoir	2.11	2.57	3.89	4.90	6.43	8.34	9.82	9.22	7.42	5.33	3.27	2.51

Figure 6. Monthly Mean Evaporation in the Vicinity of Borrego Valley, California.

area around Borrego Sink. Typical vegetation in the surrounding mountains ranges from juniper and pinyon pine on some of the desert peaks, to forests of oak, pine and cedar trees in the more humid mountains to the west.

Surface Water Drainages

The primary sources of recharge to the Borrego Valley groundwater basin are the multiple creeks and intermittent streams that drain to Borrego Valley from the surrounding mountainous areas, comprising more than 400 square miles of watershed (Figure 3). For the purposes of this study, the entire Borrego watershed has been divided into 15 drainage areas, also referred to as sub-basins, based on topographic divides observed on United States Geological Survey (USGS) 1:100,000 scale topographic maps of Borrego Valley and Palm Springs. Each of the drainage areas, which have been informally named, drain a discrete portion of the watershed. In some cases, where a single larger sub-basin could be interpreted, two or more smaller drainage areas were identified based on locations of surface water gauging stations. For example, runoff from South Coyote Canyon is tributary to Coyote Creek downstream of the former surface water gauging station location on Coyote Creek; therefore South Coyote Canyon was identified as a separate drainage area from the Coyote Creek sub-basin (Figure 3). This division was made so that gauging data from the station would accurately represent the drainage area contributing surface water flow to that station. Historically, surface water flow into Borrego Valley has been gauged from three of the sub-basins. Surface water gauging continues today at only one station located along Borrego Palm Creek (Figure 3).

Land and Water Use

Historically, Borrego Valley has been primarily an agricultural community. Although agricultural irrigation remains the single most intensive use of groundwater, the valley has gradually changed since 1960 to an accumulation of farms, retirement communities and other residential homes, and golf resorts (California Department of Water Resources [DWR], 1984b). For the year 2000, it is estimated that 62 percent of the groundwater use in Borrego Valley was for agricultural irrigation, 22 percent for recreational purposes (golf course irrigation), and 16 percent for municipal supply to urban developments. Most of the land in Borrego Valley is privately owned (Moyle, 1982). Some land around the edge of the valley and all the mountainous areas immediately surrounding the valley are within the Anza Borrego Desert State Park. In fact, the greater Borrego Springs area is completely surrounded and encompassed by state park land. Most of the land within the peripheral portions of the Borrego Watershed that is outside the State Park boundary is national forest, Indian reservation, or other private land.

Previous Studies

The geology, hydrogeology and water resources of Borrego Valley have been studied and reported by various authors since the early 1900's. Early publications typically reported locations of watering places in the desert region in and around Borrego Valley (Mendenhall, 1909; Waring 1915; and Brown, 1923). After 1945, there was an influx of people to Borrego Valley and many wells were drilled to support the growing agricultural and municipal water demand (Moyle, 1982). More recent work by federal, state and local agencies provided the most pertinent information for this study, and are detailed below.

W.L. Burnham (1954) inventoried water well data in the Borrego Valley and surrounding area. The Burnham (1954) report included summaries of driller's logs for wells that were on file at the United States Geological Survey (USGS) at the time of the report. Moyle (1968) compiled available water well and geologic data in Borrego Valley and the surrounding area during a groundwater investigation to support planned utilization and groundwater development in the area. The Moyle (1968) report also contained summaries of driller's logs to supplement those published by Burnham (1954). Water use in Borrego Valley and the adequacy of future water supply was first addressed by the U.S. Bureau of Reclamation (1968, 1972).

In 1972, R.L. Threet prepared a report of his study on the hydrogeology of southern Borrego Valley for the Digiorgio Corporation. This study was directed at evaluating water resources in southern Borrego Valley in support of the then proposed Rams Hill Development (Threet, 1972). Throughout the remainder of the 1970's, several reports were completed to evaluate groundwater resources in Borrego Valley in support of development plans for the valley, primarily for the proposed Rams Hill Development. These documents were reviewed for pertinent information regarding the aquifer system and recharge estimates.

In 1982, the USGS, in cooperation with the County of San Diego, completed the first of an anticipated three-phase study to evaluate the water resources of Borrego Valley and vicinity. The purpose of the phase 1 study was to define the geologic and hydrologic characteristics of the basin, to be used as the conceptual model for development of a computer groundwater flow model (phase 2). Moyle (1982) conceptualized a simplified three-layer aquifer system based largely on the distribution of specific capacity reported for wells throughout the valley. The aquifer system described by Moyle (1982) was comprised of (from oldest to youngest) the Miocene-Pliocene Imperial Formation, which, where known to be penetrated by wells, generally yields small amounts of high salinity water, the Palm Spring Formation, which is intermediate in water quality and yield between the older Imperial Formation and the younger basin alluvium, and the alluvium that produces the majority of water to wells in the valley.

In cooperation with the USGS and the County of San Diego, DWR prepared five technical information reports (DWR, 1981, 1983a, 1983b, 1983c, and 1984a) focusing on recharge rates, future water demand, and alternative supplies of water for Borrego, which were summarized in a final report (DWR, 1984b).

In 1988, the USGS, in cooperation with the County of San Diego and DWR, completed phase 2 of the anticipated three-phase study evaluating groundwater resources in Borrego Valley (Mitten, et al., 1988). Phase 2 of the USGS study consisted of development of a numerical groundwater flow model based on the simplified conceptualization of the aquifer system described by Moyle (1982). Hydraulic properties were assumed uniform within each layer, with hydraulic conductivity and specific yield decreasing from the shallowest to the deepest layer, as described by Moyle (1982). Groundwater recharge was simulated as constant with time using calculated average rates based on measured and estimated streamflow into Borrego Valley, and a small amount of groundwater underflow. The Coyote Creek Fault was treated as a no-flow boundary based on observed differences in water levels on either side of the fault. The planned phase 3 of the study was to use the model developed by USGS to evaluate future groundwater management scenarios for Borrego Valley. The phase 3 report is not known to have been completed.

The most recent work involving the evaluation of water resources in Borrego Valley is a draft groundwater management study report of a technical committee to the Borrego Water District (BWD, 2001). The technical committee report had three primary purposes: (1) to summarize and present findings of various studies that have been completed about the aquifer, (2) to make projections regarding the future use of the aquifer and potential related impacts, and (3) to evaluate the feasibility and effectiveness of various alternatives presented to the committee to mitigate the overdraft of the aquifer. The technical committee report was prepared under California Assembly Bill 3030 (AB 3030). The intent of AB 3030 was for large water users to reach voluntary agreement regarding the use of groundwater in a basin. An alternative to this type of planning approach, if voluntary agreement is not reached, is legal intervention and adjudication of water rights within the basin.

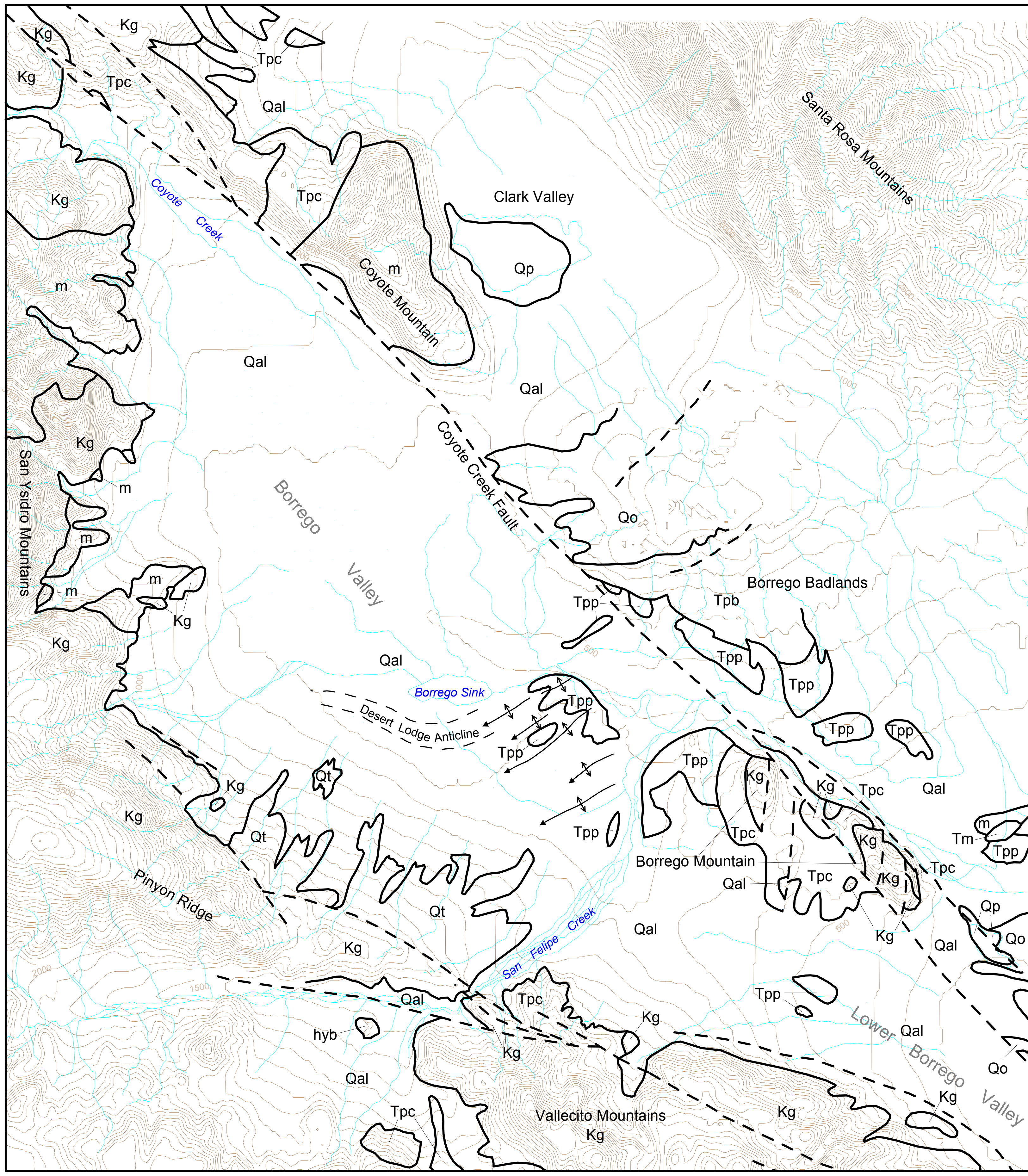
CHAPTER II

GEOLOGY

The geology of Borrego Valley and the vicinity has been mapped and described by several authors. The following summary of geologic units found within or in the vicinity of Borrego Valley is based principally on the work of the California Division of Mines and Geology (CDMG) (1959 and 1977), Dibblee (1954 and 1984), Moyle (1982), and Threet (1972). In addition, limited information was taken from other sources. A map of the surface geology in and around the perimeter of Borrego Valley is provided (modified from the California Division of Mines and Geology, 1959; Dibblee, 1984; and Threet, 1972) (Figure 7).

Basement Complex

The basement complex is the oldest geologic unit in the vicinity of Borrego Valley and is comprised of the Cretaceous granitic and the Triassic or older metasedimentary rocks of the Southern California Batholith. In Cretaceous time, the batholith intruded into what are now the surrounding mountains north, west and south of Borrego Valley. The Cretaceous granitic rocks are generally described as quartz-diorite or tonalite with minor granodiorite, and granite. The older metasedimentary rocks have been described as remnants of the roof pendant of older rocks that were intruded into during Cretaceous time by the batholithic granitic rocks. The metasedimentary rocks of northeastern San Diego County are generally described as biotite schist, gneiss, quartzite, with sparse limestone and dolomite. An interesting contact between the metasedimentary rocks and granitic rocks can be clearly seen in the Borrego Palm Canyon area and on the southeast flanks of Indian Head Mountain, where the metasedimentary rocks have the appearance of being pushed and up tilted towards the valley as the granitic rocks intruded from beneath. In this study, the metasedimentary rocks and granitic rocks are collectively referred to as the basement complex as they are both hard crystalline rocks with limited water bearing capacity. The basement complex is the ultimate base of the aquifer system and crops out on the north, west and south of the basin as well as at Borrego Mountain (Figure 7). A regional unconformity occurs between the basement complex and overlying Tertiary rocks.



Modified From: California Division of Mines and Geology, 1959; Dibblee, 1984; and Threet, 1972.

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 7. Local Geology, Borrego Valley, California.

Imperial Formation

The Tertiary Imperial Formation crops out east of Borrego Valley, on Squaw Peak and further east in the Shell Reef area of the San Felipe Hills. The Imperial Formation may occur at depth in Borrego Valley, overlying the basement complex. The Imperial Formation is Miocene or possibly early Pliocene in age and generally described as light tan, yellow or gray claystone with lesser thin interbeds of tan to light gray arkosic sandstone and thin dark gray calcareous reefs of oyster shells (CDMG, 1977; Dibblee, 1954 and 1984). The Imperial Formation was deposited in a shallow marine environment when, in late Miocene and/or Pliocene time, the northern Gulf of California had inundated what is now the Imperial Valley (Dibblee, 1984). Though the Imperial Formation is stratigraphically beneath the Palm Spring Formation, it is unknown to what extent it may be found at depth in Borrego Valley. A single well in Borrego Valley, 10S/5E 25R1, is reported to have encountered shells during drilling which would be consistent with the Imperial Formation. The published drillers log for this well reports shells in the bottom 75 feet of the boring, from a depth of 430 feet to 505 feet below ground surface at that location (Moyle, 1968). No other evidence of the Imperial Formation has been found in driller's logs from wells in Borrego Valley.

Canebrake Conglomerate

In the vicinity of Borrego Valley, the Tertiary Canebrake Conglomerate crops out near the top and on the western slopes of Coyote Mountain, on the northeastern slopes of Sunset Mountain, near where San Felipe Creek emerges from the narrows and enters the valley, and all around the West and East Buttes of Borrego Mountain (Figure 7). The Canebrake Conglomerate is early Pliocene in age and, on Borrego Mountain, is described as a gray cobble conglomerate of granitic and gneissic detritus. It is interpreted as the coarse marginal facies of the Palm Spring Formation and was deposited by "torrential storms as alluvial fans of basement detritus from the rising Peninsular Range terrane onto the western margin of the subsiding Imperial basin" (Dibblee, 1984). The Canebrake Conglomerate may occur at depth in Borrego Valley, stratigraphically above the Imperial Formation (if present) or resting directly on crystalline basement rock, as is observed on Coyote Mountain and Borrego Mountain in Borrego Valley and in the Santa Rosa Mountains to the east of Borrego Valley.

Palm Spring Formation

The Tertiary Palm Spring Formation crops out in Borrego Valley to the east of Desert Lodge and the town of Borrego, near the Borrego Air Ranch and Sleepy Hollow, and also flanking the western slopes of Borrego Mountain's West Butte (Figure 7). The Palm Spring Formation is Pliocene in age and is generally described as terrestrial interbedded light gray arkosic sandstone and red claystone. It is said to generally grade downward into the marine Imperial Formation, marginally into the Canebrake Conglomerate, and Upward into the Borrego lacustrine beds (Dibblee, 1954 and 1984). The Palm Spring Formation is also encountered in several wells throughout the southern portion of Borrego Valley, typically at greater depths with distance from the surface outcrops. The lower portions of the Palm Spring formation lie stratigraphically adjacent to the Canebrake Conglomerate as an inter-fingering lateral facies while younger portions of the Palm Spring Formation lie stratigraphically above the Canebrake Conglomerate, as is observed at Borrego Mountain. The Palm Spring Formation may lie directly on crystalline basement rock at depth in portions of Borrego Valley, where the Canebrake Conglomerate and Imperial Formation are absent.

Older Alluvium

The Quaternary older alluvium underlies most of the valley floor of the northern and central portions of the valley. It is absent, thin or unsaturated in the area from central Borrego Valley southward towards the vicinity of the Palm Spring Formation outcrops. The Older Alluvium is Pleistocene to Holocene in age, and is comprised of moderately sorted gravel, sand, silt, and clay. It was deposited primarily as alluvial fan and intermittent stream deposits. It is generally unconsolidated but in some areas may be slightly cemented. This unit is relatively permeable and is saturated in most areas, comprising the principal water bearing unit of the aquifer system (Moyle, 1982).

Lacustrine Deposits

Lacustrine deposits are present at or near the surface in the central portion of Borrego Valley. This unit is Pleistocene to Holocene in age and is generally comprised of silt and clay with thin interbeds of fine sand. The lacustrine deposits were deposited at the topographically low area in the central portion of the valley, in a low energy, shallow fresh water environment, such as a lake or delta. No evidence of the accumulation of evaporites has been observed in driller's logs that penetrated this unit.

Younger Alluvium

Quaternary younger alluvium is present at the surface throughout the majority of Borrego Valley, absent only where the lacustrine unit or Palm Spring Formation is exposed at the surface. The younger alluvium is Holocene age and is comprised of unconsolidated gravel, sand, silt, and clay. It is partially saturated throughout much of the northern portion of the valley and readily yields water to wells screened in the coarser portions of this unit. It was deposited primarily by alluvial fans and intermittent streams.

Additional Geologic Units in the Vicinity of Borrego Valley

The Borrego Formation and Ocotillo Conglomerate are found extensively throughout the badlands east of Borrego Valley. These formations are described in the following sections.

Borrego Formation

The Tertiary Borrego Formation is late Pliocene to early Pleistocene in age. The Borrego Formation is not known to occur in Borrego Valley but is found to the east of Borrego Valley, across the Coyote Creek Fault, throughout the Borrego Badlands. It is comprised of light gray bedded to massive claystone and thin interbeds of tan to light gray sandstone. The Borrego Formation is interpreted as the lacustrine facies of the Palm Spring Formation (Dibblee, 1984).

Ocotillo Conglomerate

The Quaternary Ocotillo Conglomerate is Pleistocene in age. It is not known to occur in Borrego Valley but is found to the east of Borrego Valley across the Coyote Creek Fault and throughout the Borrego Badlands where it lies stratigraphically over the Borrego Formation. It is described as a poorly bedded light gray granitic pebble-cobble conglomerate (Dibblee, 1984).

Structural Features

The Late Cenozoic sedimentary rocks of the Imperial Basin, including Borrego Valley, have been severely deformed by movements along faults of the San Jacinto Fault Zone. Portions of the basement complex have been elevated and shifted along branches of the fault zone causing the sedimentary series to buckle into a series of folds throughout the area. Notably, the basement rocks are exposed at Borrego Mountain and movement along the Coyote Creek Fault has buckled the sedimentary rocks into a series of folds to the northwest of Borrego Mountain. This can be seen where the Palm Spring Formation has been elevated to the surface and buckled into the series of folds in the vicinity of Sleepy Hollow (Figure 7).

Faults

Borrego Valley is located on the edge of the San Jacinto Fault zone, characterized by a series of right-lateral, strike slip faults which trend to the northwest (Figure 8). The Coyote Creek Fault is the southwestern strand of the San Jacinto Fault zone, which runs along the northeastern edge of Borrego Valley. It is the largest fault in this area and has an estimated 3 miles of right-slip displacement in the basement complex northwest of Borrego Valley (Dibblee, 1984). The Coyote Creek Fault is interpreted to be a partial barrier to groundwater flow based on high water level gradients across the fault, though published water level maps indicate areas where groundwater flow may be occurring across the fault, generally at areas where the alluvium is expected to be relatively thick (Moyle, 1982). For example, groundwater may be discharging across the fault to the north of Borrego Mountain, beneath the approximate course of San Felipe Creek, rather than flowing south along the fault directly into Lower Borrego Valley (discussed in the next chapter) (Figure 7).

Folds

As mentioned above, movements along the Coyote Creek Fault have buckled the sedimentary rocks in the southeastern portion of the valley. Many of these folds were mapped by Dibblee (1984) as a series of southwestward plunging anticlines and synclines (Figure 7). These were later referred as the Sleepy Hollow folds because of their proximity to the Sleepy Hollow area of Borrego Valley; in fact, Sleepy Hollow itself lies within a topographic trough of one of the synclines (Threet, 1995). The Palm Spring Formation has been mapped along the central axis of most of the anticlines (Dibblee, 1984). Additionally, during a study on the hydrogeology of Southern Borrego Valley, the westward projection of

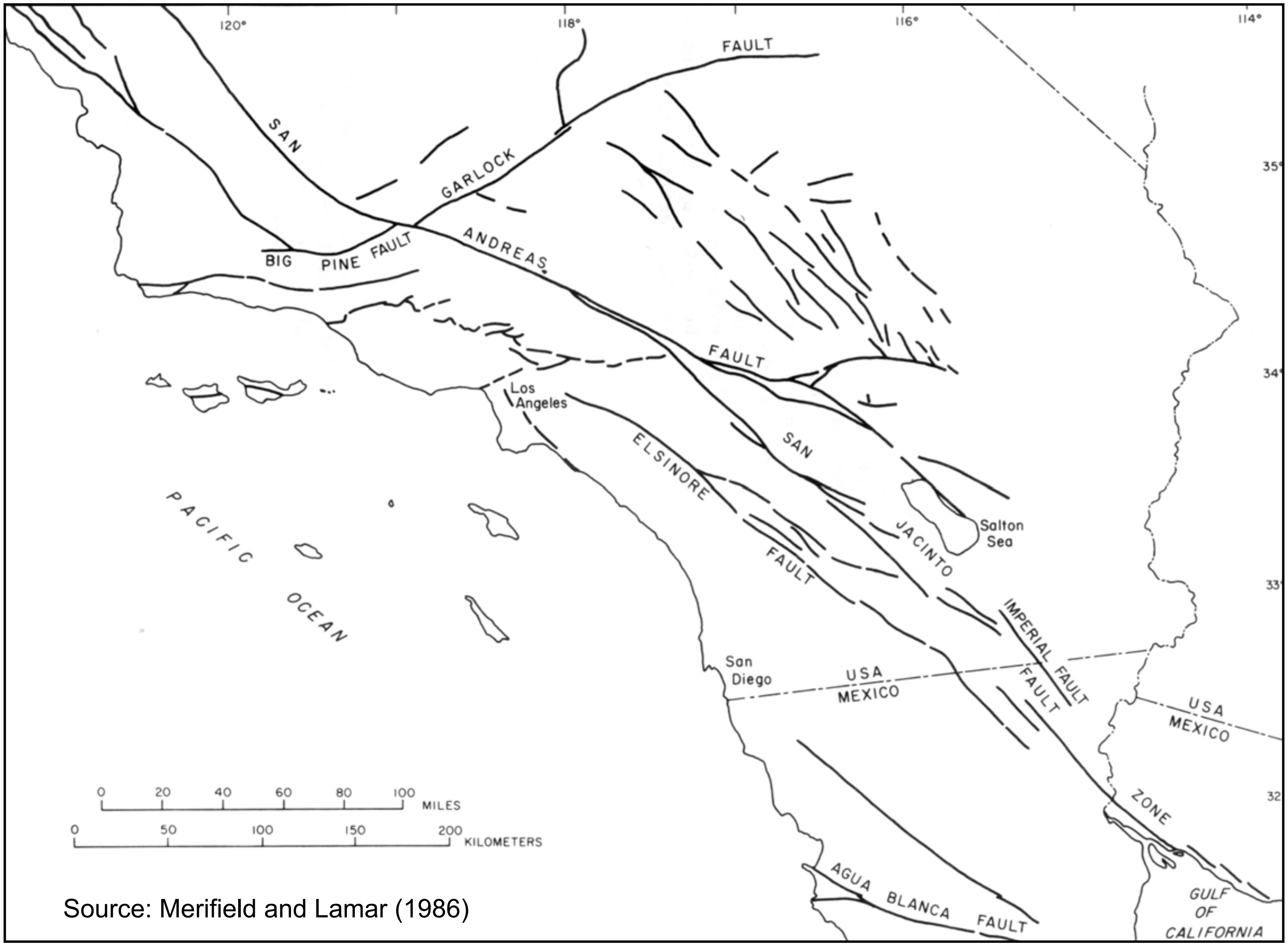


Figure 8. Major Faults in Southern California.

one the northernmost in the series of anticlines was mapped based on the distribution of "hard dry red clays" in driller's logs, which is associated with the Palm Spring Formation (Threet, 1972). This "clay cored anticline", named the *Desert Lodge Anticline*, has been described as being somewhat of a barrier to groundwater flow (Threet, 1972).

CHAPTER III

HYDROGEOLOGY

A conceptual model of the Borrego Valley hydrogeologic system was developed based on the definition and distribution of hydrostratigraphic units within the aquifer system. This conceptual model development included the identification of hydrostratigraphic units and interpretation of their distribution throughout the groundwater basin, definition of the distribution of hydraulic properties within the hydrostratigraphic units, and an evaluation of water levels and groundwater flow through the aquifer system. The objectives of the conceptual model development were ultimately to provide the basis for development of a numerical groundwater flow model (Henderson, 2001). As such, defined hydrostratigraphic units did not coincide exactly with geologic units, rather, nearly continuous hydrostratigraphic units with varying geologic materials and hydraulic properties were defined regardless of the continuity of the geologic formation. Exceptions to this principle are (1) the hydrostratigraphic unit representing the Palm Spring Formation and any potential underlying formation was “pinched out” against bedrock within the basin; (2) hydrostratigraphic units stratigraphically above the Palm Spring Formation were “pinched out” where the Palm Spring Formation crops out at the surface; and (3) though no other unit was forced to pinch out, during interpolation and projection of hydrostratigraphic layer surfaces, individual units were allowed to pinch out as results from the interpolation indicated, for example, when layers pinched against bedrock or a younger or older unit.

Definition of Hydrostratigraphic Units

Definition of the conceptual hydrogeologic model was based to a large degree on the stratigraphic interpretation of driller’s logs from well borings throughout Borrego Valley. In addition, new interpretations of bedrock depth throughout the valley have been made by others, based on evaluation of gravity data, and incorporated into the conceptual model (Agbabian, 1997; Martin, 1995; Henderson, 2001). Available driller’s logs for wells in Borrego Valley were obtained from the California Department of Water Resources (DWR) and from published literature (Burnham, 1954; Moyle, 1968; Threet, 1972). Of the more than 340 wells known to have been drilled in Borrego Valley and vicinity (Figure 2), driller’s logs or other lithologic information were available for approximately 130 wells, which were used to develop the conceptual model of the basin. Ten hydrogeologic cross-sections were constructed across Borrego Valley, the locations of which were based on the distribution of wells with available lithologic information (Figure 9). The elevations of discrete hydrostratigraphic units were estimated based on the lithologic description on each log.

In general, layer 1 represents the younger alluvium. It is discontinuous throughout the valley, missing where older units are exposed at the surface, and effectively pinched out where the base of the layer is above the water table. Layer 2 represents the lacustrine unit and intermediate aged alluvium. Layer 2 is also discontinuous and, where present, is generally comprised of lacustrine deposits near the center of the basin and intermediate aged alluvium around the perimeter. Layer 3 represents the older alluvium. Layer 3 is missing throughout much of southern Borrego Valley, where the Palm Spring Formation is at or near the surface. Layer 4 represents the Palm Spring Formation and possibly underlying Imperial Formation. It occurs at or near the surface in the southern portions of Borrego Valley and at depth throughout most of the valley. The geometry of each of these units was interpreted as follows.

Elevation of the bottom of the uppermost unit (layer 1) was based on interpretations of the bottom of the younger alluvium, if present, in each log. Elevation of the bottom of the second unit down from ground surface (layer 2), was either based on interpretations of the base of the lacustrine unit, where present, or the base of any other intermediate aged alluvium that was described as finer in texture than typically found elsewhere in the younger or older alluvium, if present in any log. For example, at the Borrego Springs Water Company well drilled near Borrego Springs High School in 1995 (10S/6E 32D), considerable amounts of interbedded sand, silt and clay were encountered to a depth of approximately 280 feet below ground surface, below which was encountered predominantly medium to coarse sand through the total depth of the boring, which terminated on bedrock at a depth of approximately 805 feet. At this well, layer 1 was very thin, less than 30 feet thick, and unsaturated. The elevation for the base of layer 2 was 280 feet below ground surface, the depth of the base of interbedded sand, silt and clay. Layer 2 in this area represents intermediate aged alluvium that contains considerable fine-grained materials, whereas in the central portion of the valley, where the lacustrine unit was encountered in well logs, layer 2 represents the lacustrine unit. Elevation of the bottom of the third unit down from ground surface (layer 3) was either based on interpretations of the base of the older alluvium, or the top of the Palm Spring Formation (layer 4), where present. In this manner, elevation picks

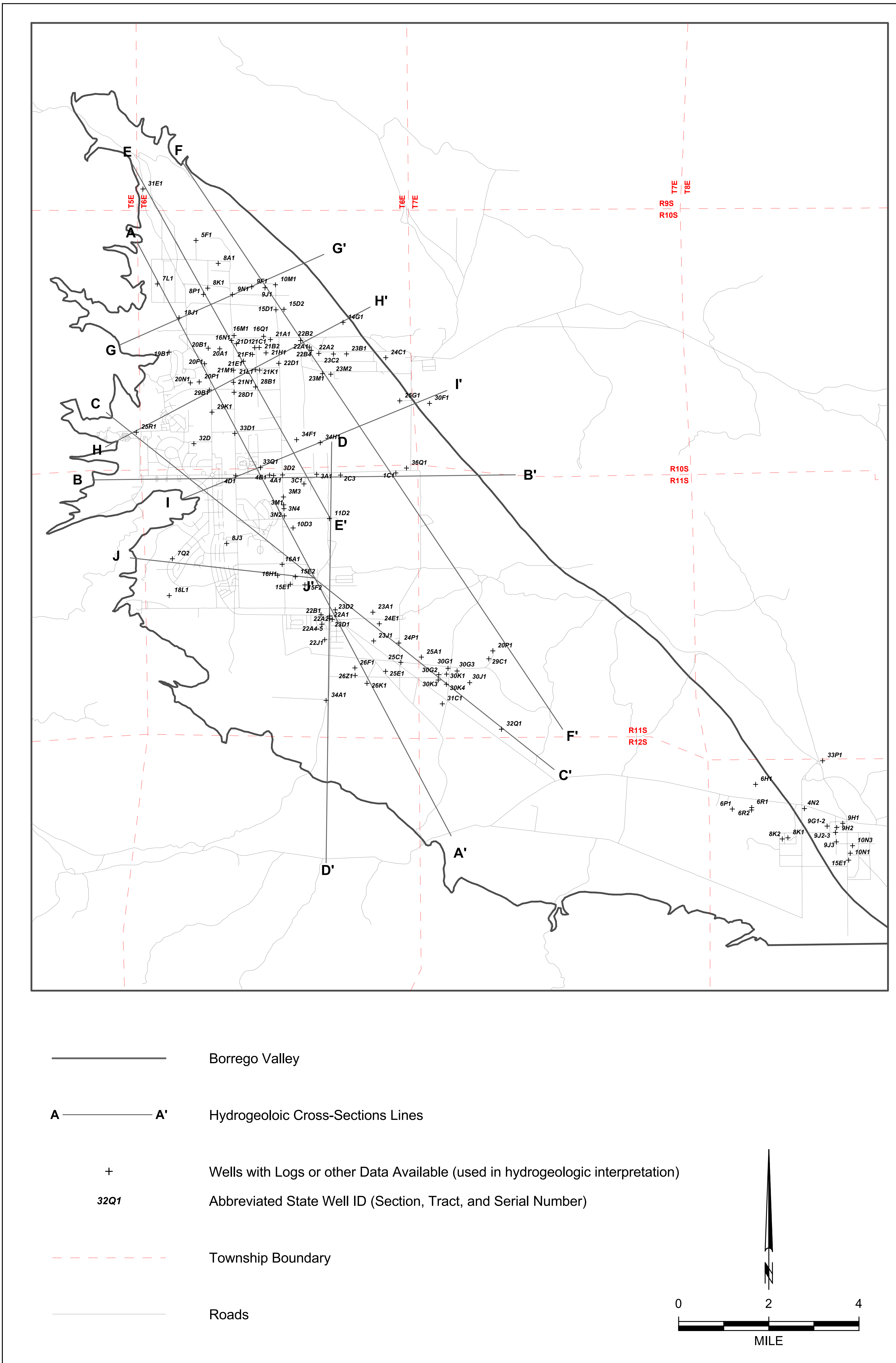


Figure 9. Well Location Map With Hydrogeologic Cross-Section Lines.

for four hydrostratigraphic units were compiled. Contour maps for the top elevation and thickness of each unit, including bedrock surface elevation, were constructed using a thin plate spline radial basis function interpolation algorithm within the computer software application Surfer[tm] (Golden Software, Inc., 2000) (Figures 10 through 18). Layer 1 ranges in thickness between 0 and 400 feet throughout the primary portions of the aquifer, and attains a maximum thickness of approximately 1,200 feet in the vicinity of San Felipe Creek. Layer 2 ranges in thickness between 0 and 600 feet and is thickest in the central portion of the valley near the Borrego Sink, where the lacustrine deposits are thickest. Layer 3 ranges in thickness between 0 and 1,000 feet throughout the primary portion of the aquifer and attains a maximum thickness of approximately 1,400 feet in the vicinity of Coyote Canyon. Layer 4, the Palm Spring and possible underlying formations, range in thickness between 0 to 4,000, feet and is thickest in the central portion of the valley where the basement rock attains its greatest depth. The blanked out areas (white patches) in Figures 10 through 18 represent areas where units are missing or of insignificant thickness. The conceptual model interpretations along each of the 10 hydrogeologic cross-sections have been plotted (Plate 1).

Lateral distribution of soil texture within each of the hydrostratigraphic units was interpreted based primarily on the descriptions of soil texture on driller's logs. For each log, the predominant grain size within each hydrostratigraphic unit was classified as one of the following textural groups: gravel, coarse sand, medium sand, fine sand, silt/clay, or interbedded combinations of these soil textures. In many cases the descriptions of sand on driller's logs did not include the modifiers: fine, medium or coarse. In these instances, medium grained sand was assumed. The distribution of texture within each hydrostratigraphic unit was interpolated between the locations associated with each of the driller's logs. In areas where driller's logs or other lithologic information was lacking, spatial sediment distributions were interpreted from generalized sedimentary facies models for alluvial fans and fluvial deposition (McCloskey and Finnemore, 1996). The interpreted textural distribution within the alluvium is presented in Figures 19 through 21, and Plate 1. Textural distribution within the alluvium is characterized by a fining inward sequence. This pattern is consistent with the depositional environments where coarser materials are generally found at areas proximal to source terrane, the mountains of the surrounding watershed, and sequentially finer materials are generally found in distal areas from the source terrane. As with Figures 10 through 18, blanked out areas (white patches) in Figures 19 through 21 represent areas where units are missing or of insignificant thickness.

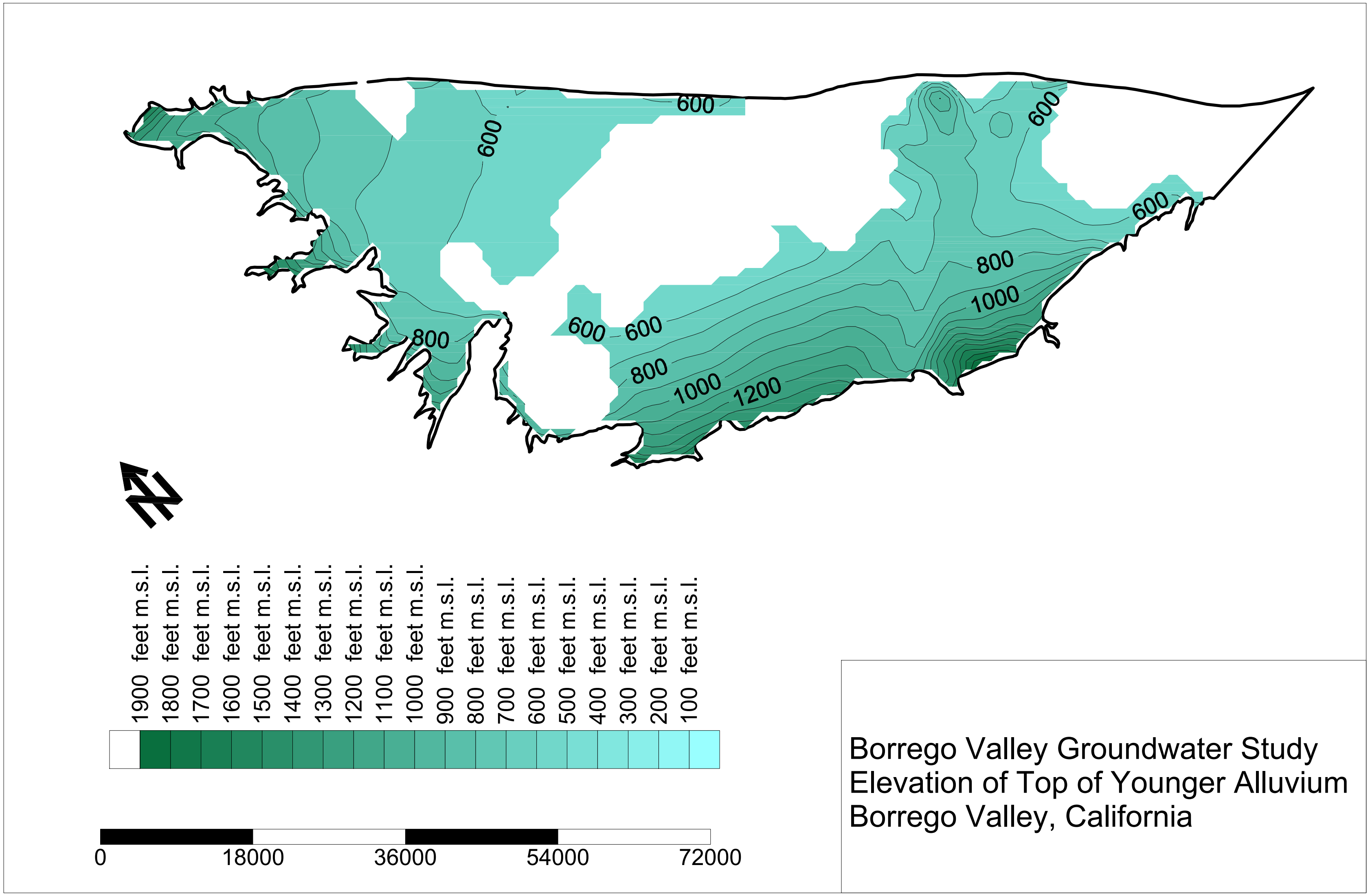


Figure 10. Elevation of Top of Younger Alluvium - Borrego Valley.

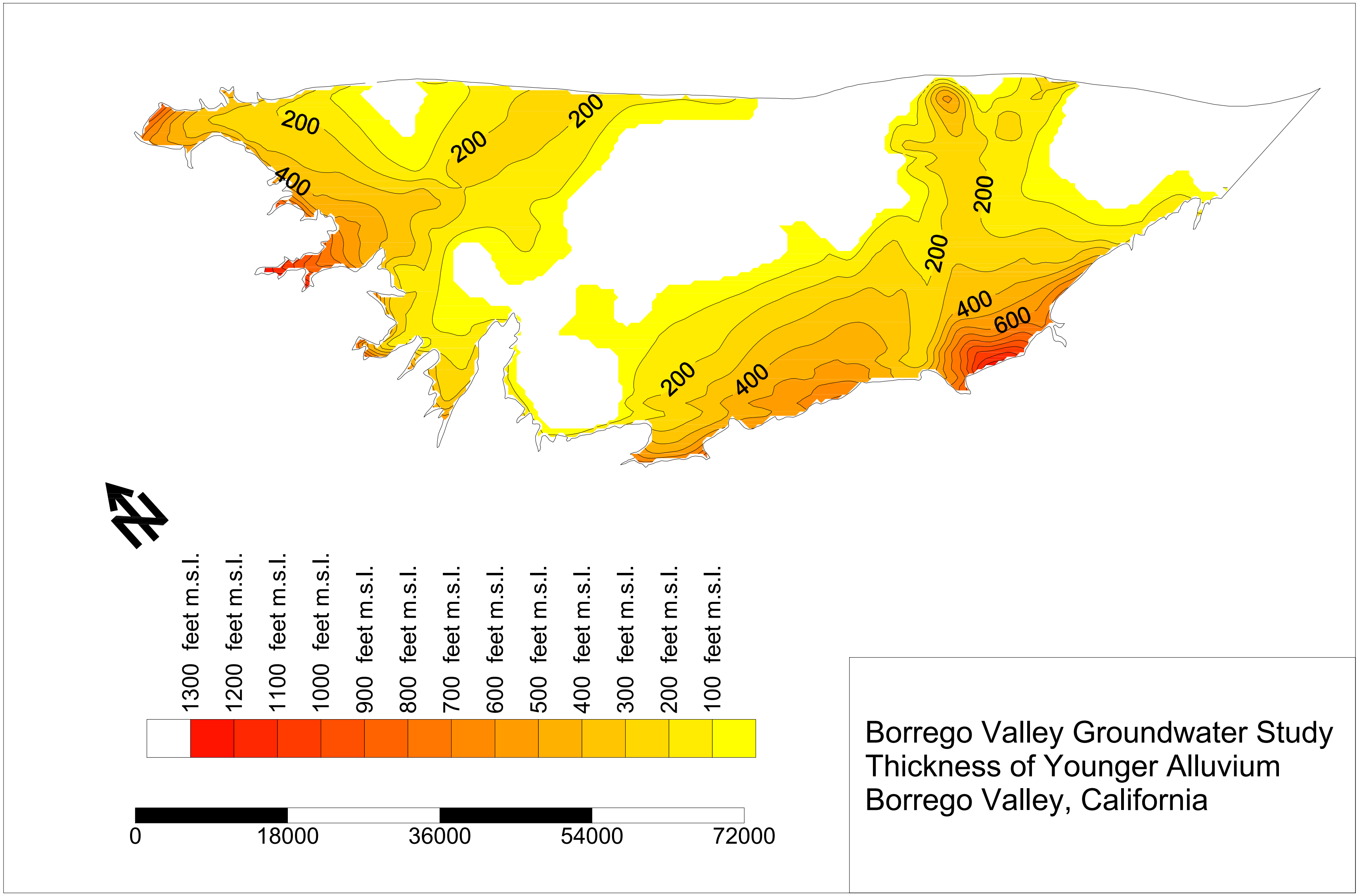


Figure 11. Thickness of Younger Alluvium - Borrego Valley.

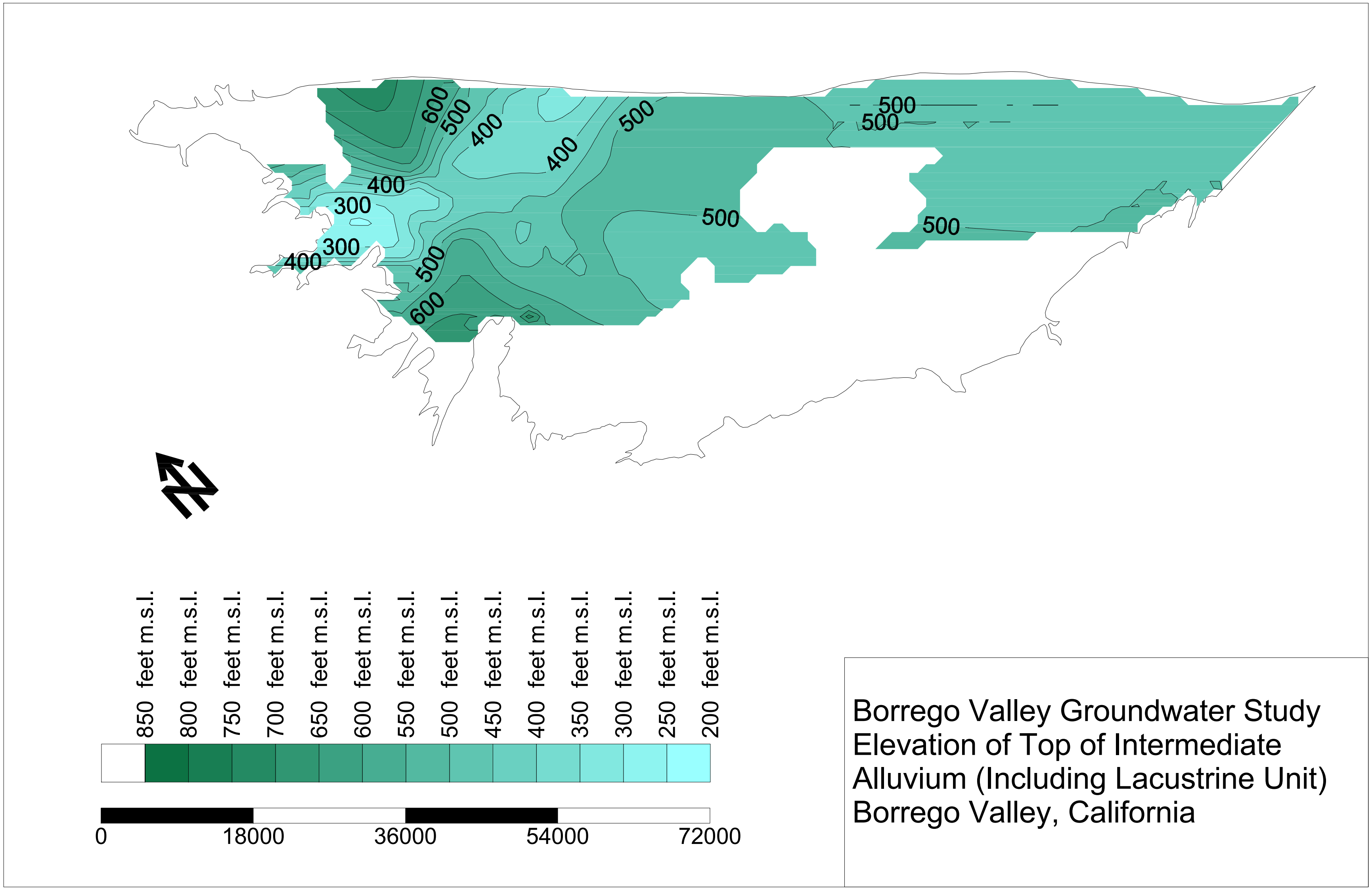


Figure 12. Elevation of Top of Intermediate Alluvium - Borrego Valley.

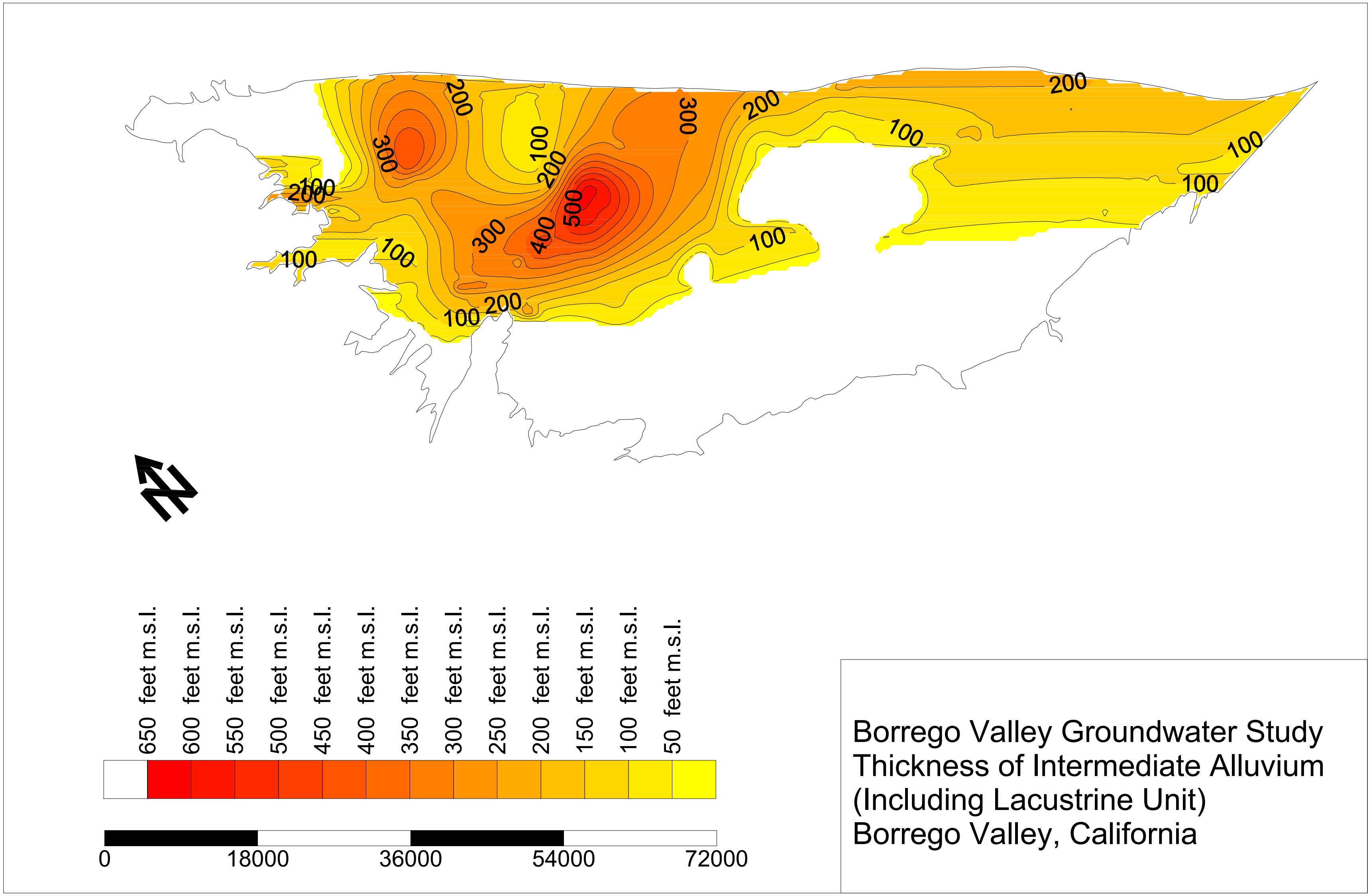
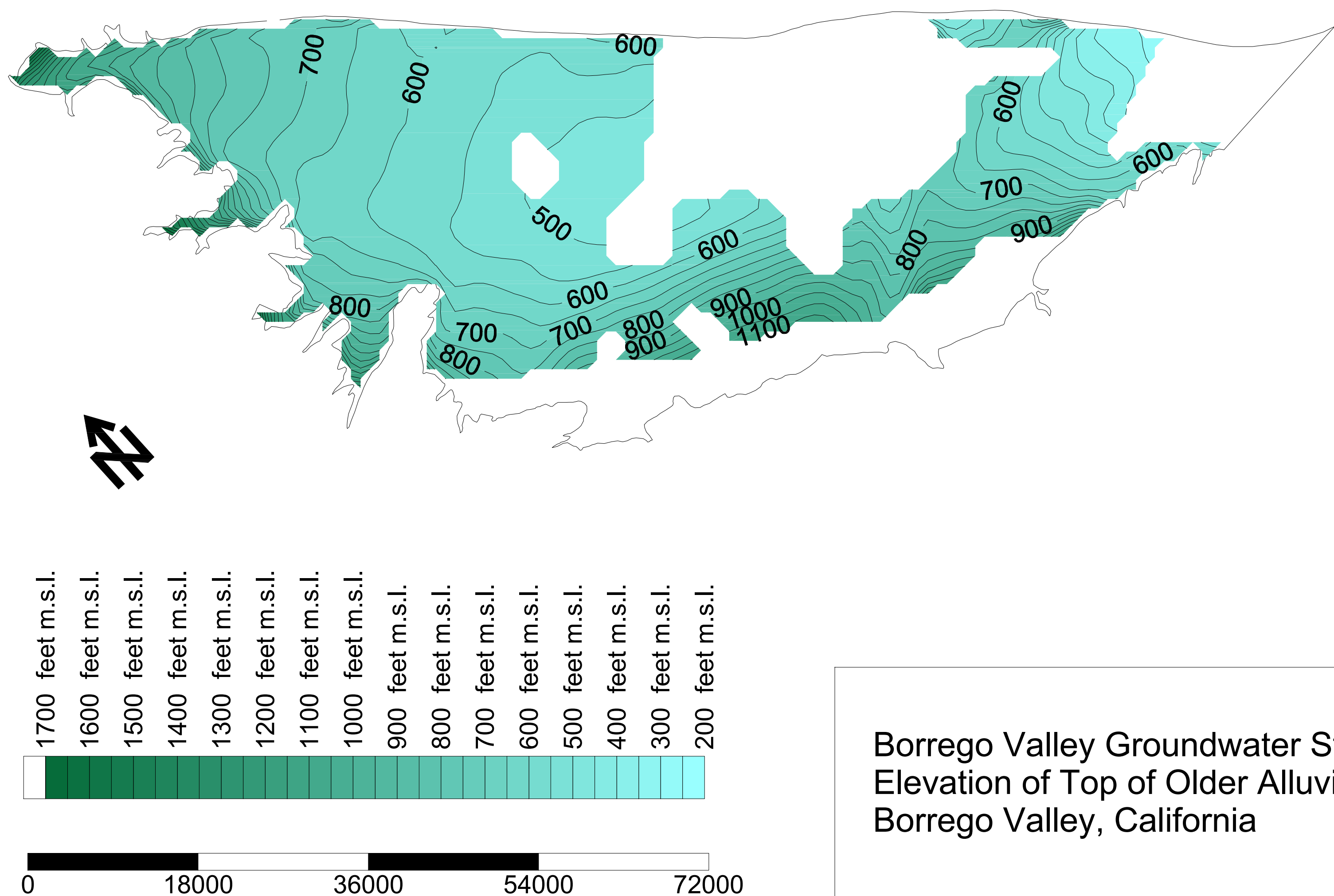


Figure 13. Thickness of Intermediate Alluvium - Borrego Valley.



Borrego Valley Groundwater Study
Elevation of Top of Older Alluvium
Borrego Valley, California

Figure 14. Elevation of Top of Older Alluvium - Borrego Valley.

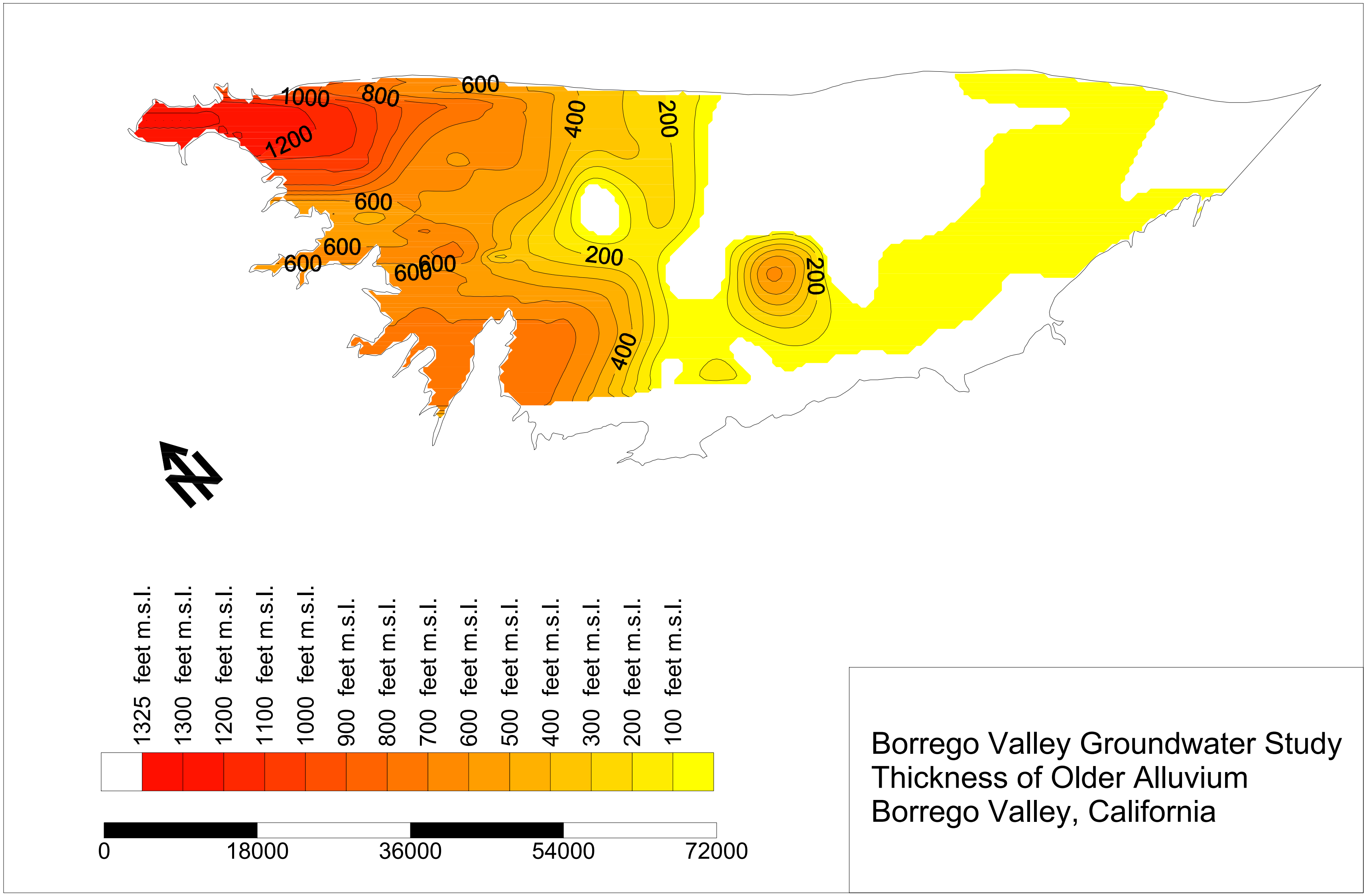


Figure 15. Thickness of Older Alluvium - Borrego Valley.

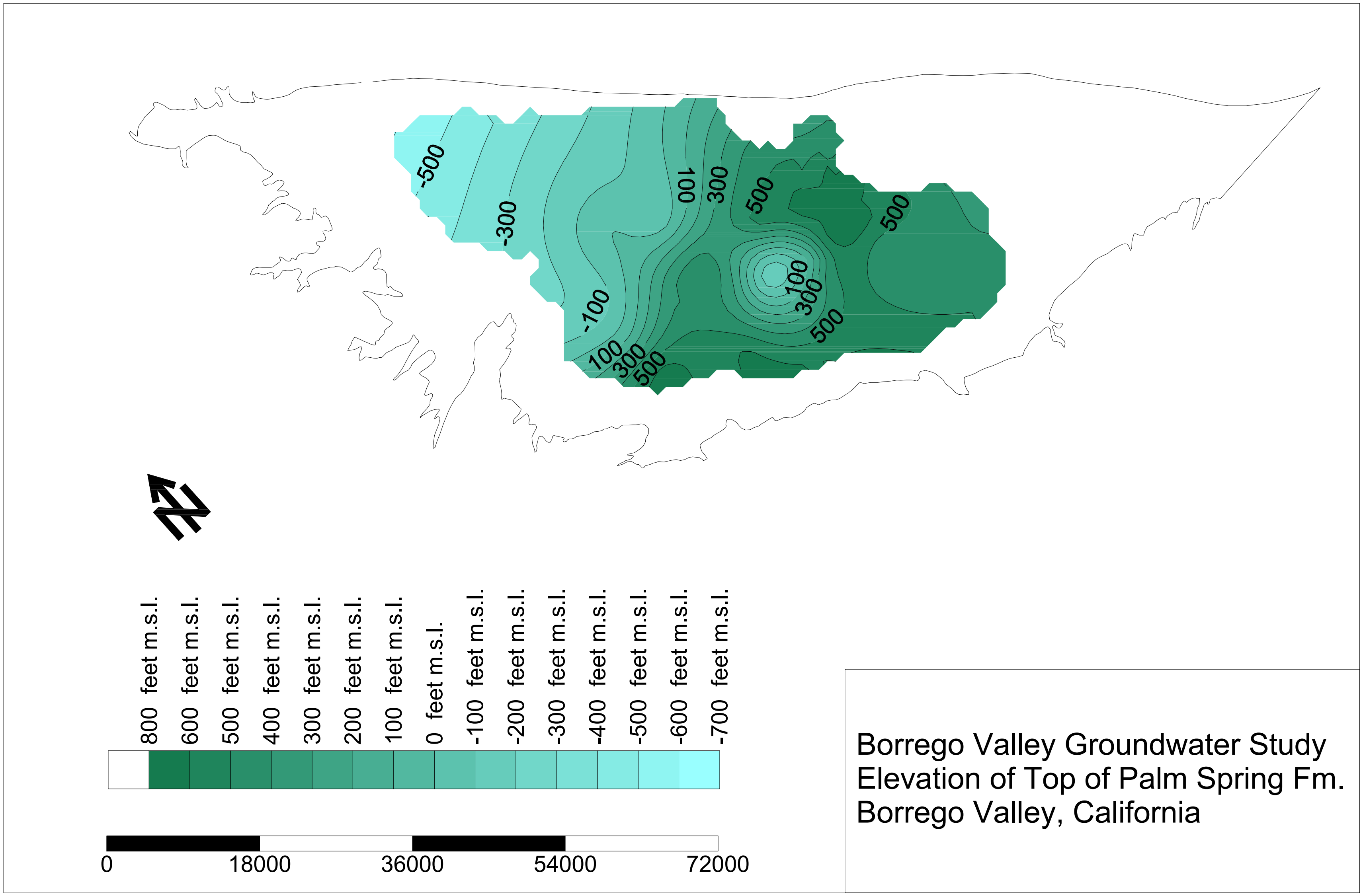


Figure 16. Elevation of Top of Palm Spring Formation - Borrego Valley.

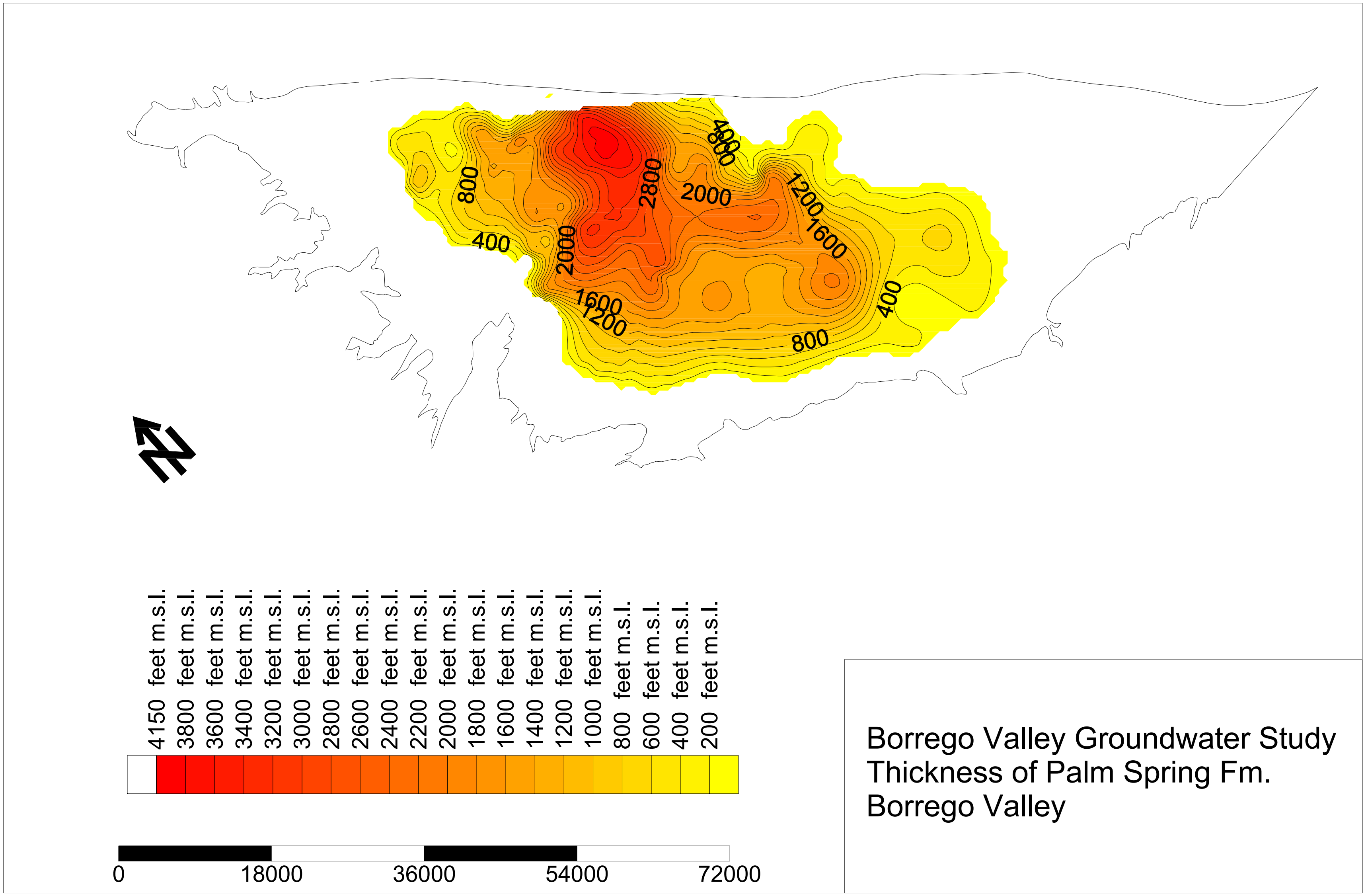


Figure 17. Thickness of Palm Spring Formation - Borrego Valley.

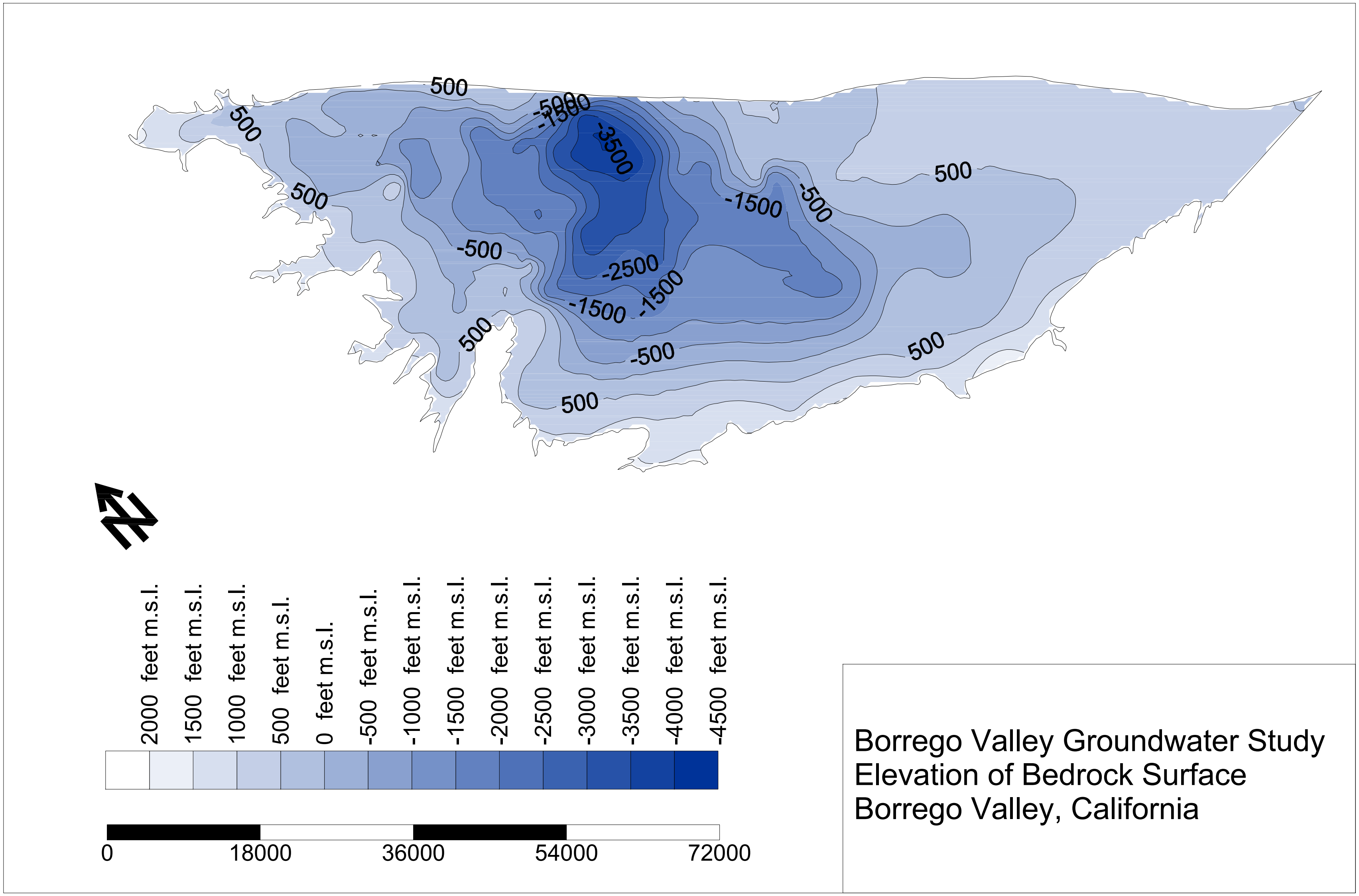


Figure 18. Top of Basement Elevation - Borrego Valley.

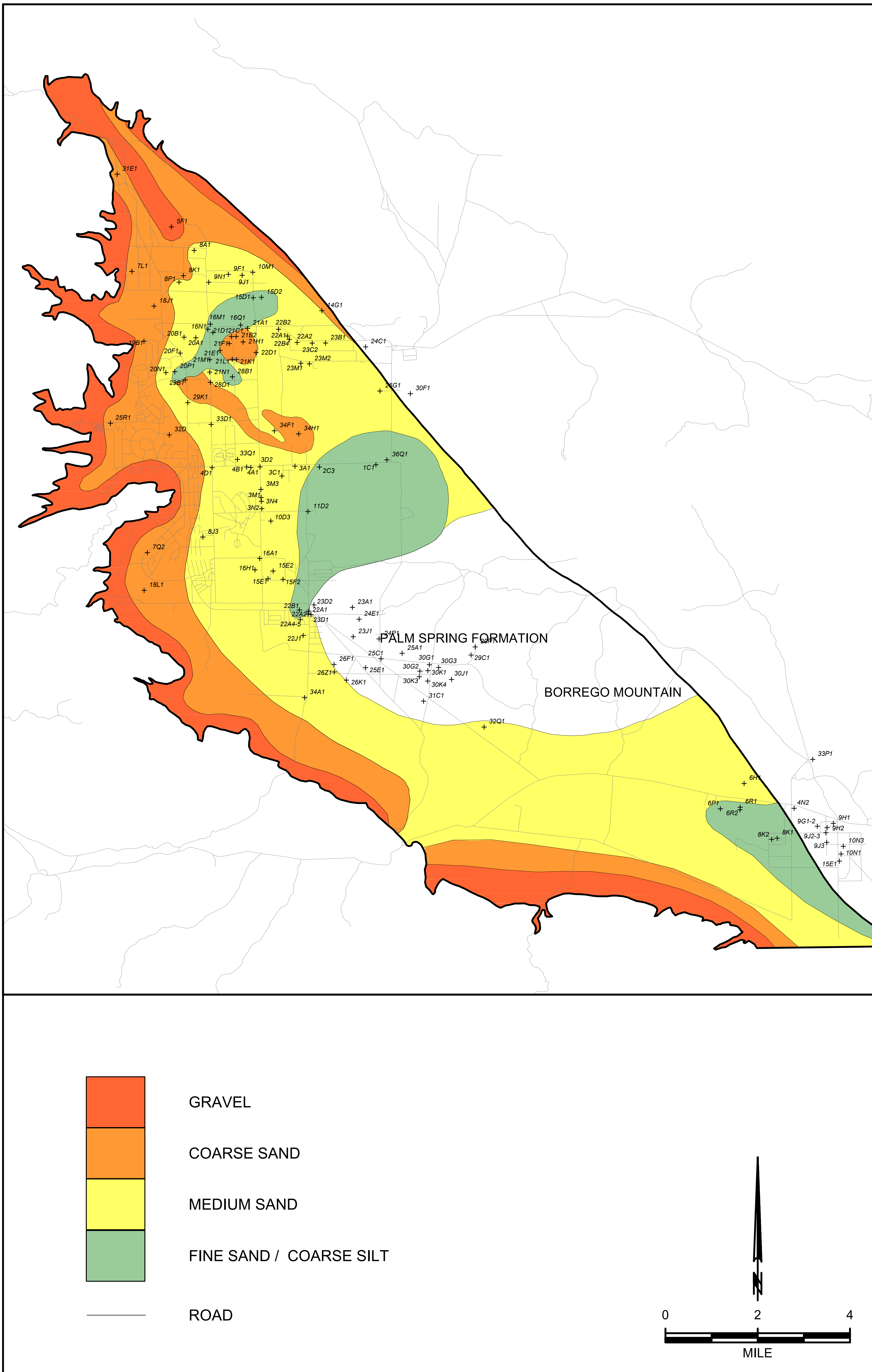


Figure 19. Distribution of Soil Texture in Younger Alluvium - Borrego Valley.

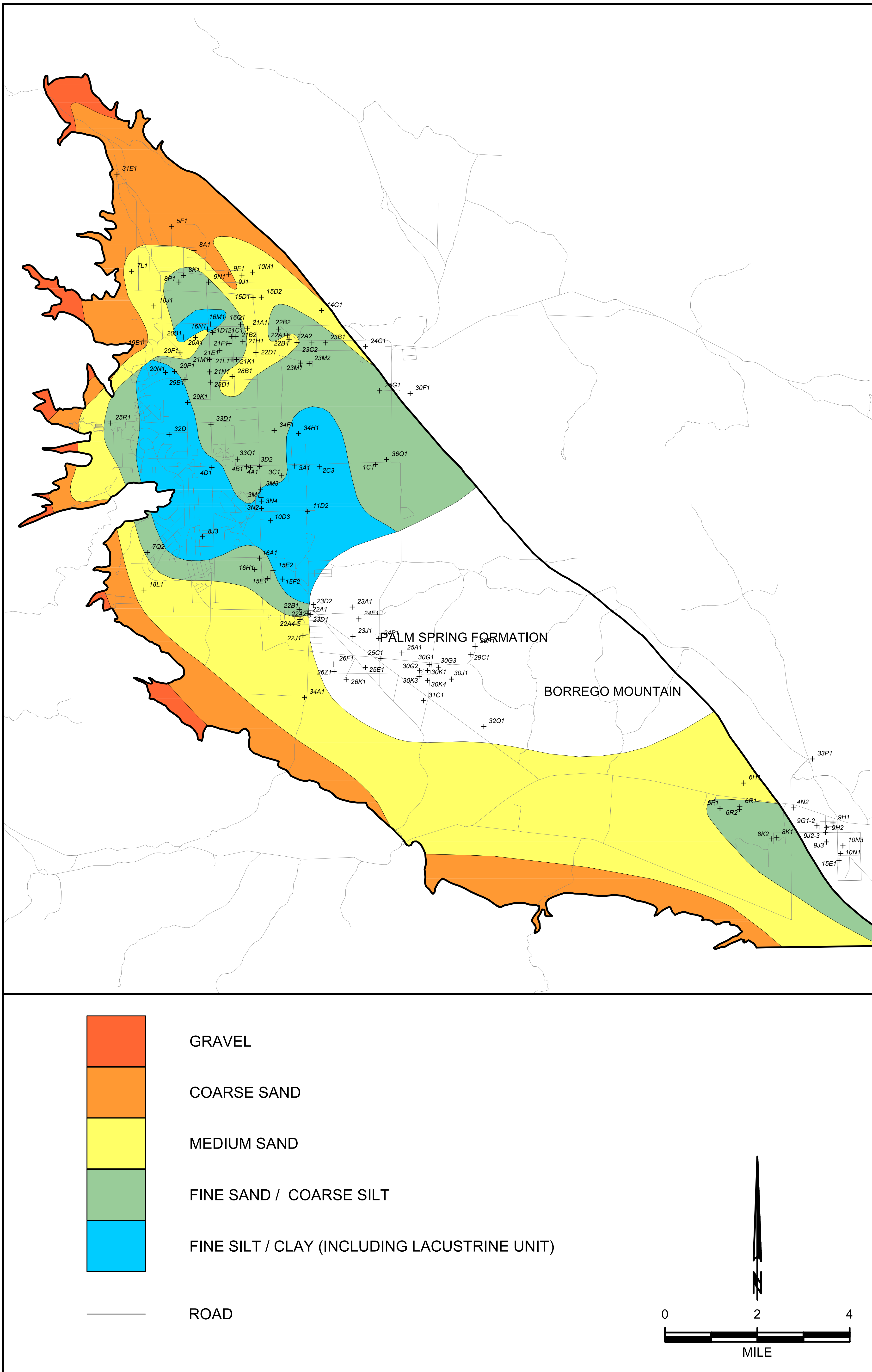


Figure 20. Distribution of Soil Texture in Intermediate Alluvium - Borrego Valley.

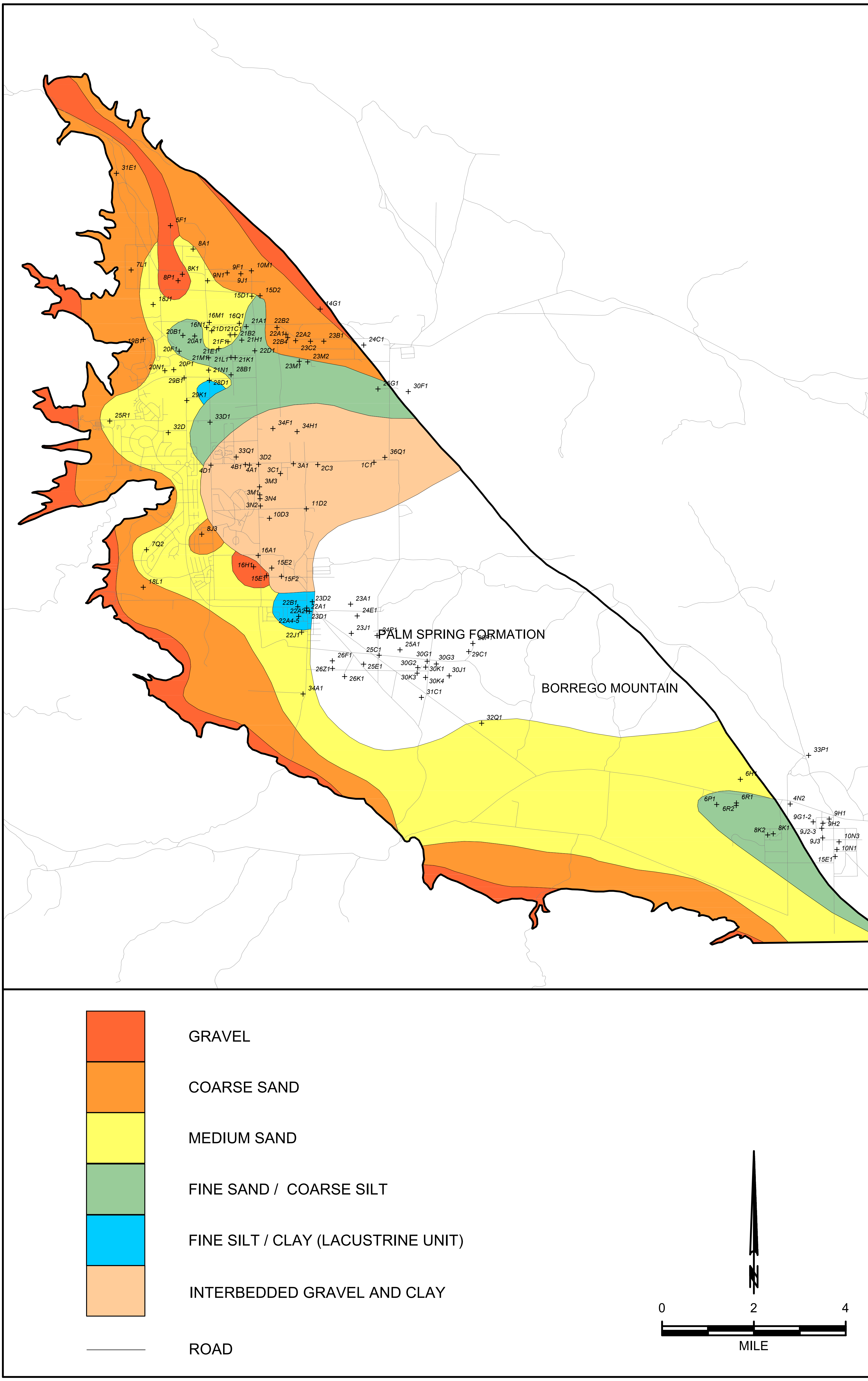


Figure 21. Distribution of Soil Texture in Older Alluvium - Borrego Valley.

The Palm Spring Formation generally consists of red clay with interbedded fine sand based on driller's logs for the relatively few wells that have been drilled into the Palm Spring Formation in southern Borrego Valley. It was assumed that this interbedded texture is representative of the Palm Spring Formation throughout Borrego Valley (Plate 1).

The conceptualization of hydrostratigraphic units described above is different from the previous conceptualization made by the USGS (Moyle, 1982), which has since been the basis for other groundwater modeling and water resource studies in Borrego Valley (DWR, 1984b; Mitten, 1988). Moyle (1982) described a three-aquifer system corresponding to the alluvium, upper Palm Spring Formation, and the combined lower Palm Spring and Imperial Formations, respectively. Each unit was described as uniform, with no variation of the physical characteristics within any of the three units. In this current study, the alluvium, comprising the upper aquifer of Moyle (1982), has been divided into three separate hydrostratigraphic units, each with varying physical characteristics based on the distribution of soil texture within the alluvium. The middle and lower aquifers of Moyle (1982), have been combined into one unit, partly because sufficient data is lacking to make clear distinction between separate hydrostratigraphic units within the Palm Spring Formation and potentially underlying Imperial Formation, and also because groundwater production from this unit is limited to relatively shallow portions of the Palm Spring Formation from a limited area in southern Borrego Valley. The current model has increased the definition of the hydrostratigraphy in the principal water bearing portions of the aquifer system, namely the alluvial aquifer.

Evaluation of Hydraulic Properties

Aquifer tests were performed to measure transmissivity at four wells throughout Borrego Valley: in northern Borrego Valley at the Bauer Wells 1 and 2, in central Borrego Valley at Borrego Springs Water Company Well 5, and in southern Borrego Valley at Borrego Water District Wells 1 and 8 (Figure 22). At each well a constant discharge rate test was performed, with water levels measured both during the drawdown and recovery phases. All aquifer test data are provided in (Appendix A). The specifics of each test are described in the following sections.

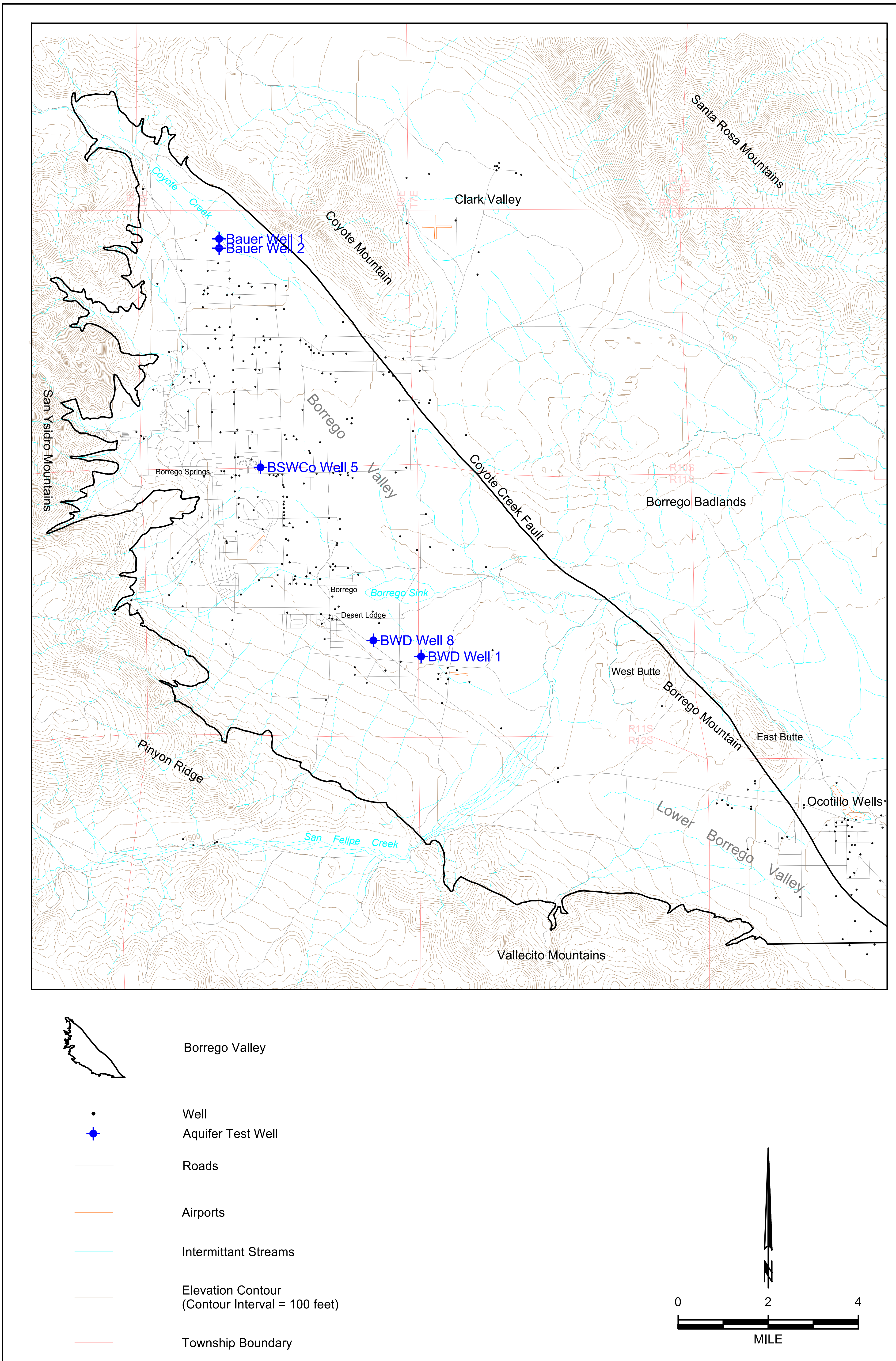


Figure 22. Location of Aquifer Test Wells.

Bauer Wells 1 and 2

Stan Bauer's wells 1 and 2 are completed in the north end of the groundwater basin, as his citrus orchards are among the northernmost in the valley. Both wells are used for irrigation of citrus orchards and pump for a limited number of hours per day based on the irrigation schedule for the citrus trees. Permission was obtained from Mr. Bauer to monitor water levels in his wells during normal pumping cycles. Well 2 is a relatively new well (constructed in 1996) that, at the time of aquifer testing, was not yet connected to the irrigation distribution system and therefore was not being pumped. However, Well 1 was routinely pumped for approximately 7 hours per day at the time of aquifer testing. The wells were examined and it was found that Well 1 (the pumping well) had no access for water level measurements, but the discharge pipe was equipped with a relatively new totalizing flowmeter (the well was constructed in 1992). Bauer Well 2 is located approximately 1,100 feet to the south from Bauer Well 1. Well 2 had adequate access for a small wire line sounder to measure water levels. Bauer Well 1 (pumped well) is screened across 370 to 390 feet, 410 to 530 feet, 550 to 690 feet, and 710 to 730 feet below ground surface, totaling 300 feet of well screen. According to the driller's log, all of the screened intervals in Well 1 are adjacent to "coarse sand" (160 feet thick), "coarse sand with some clay" (140 feet thick), or "coarse sand with bits of clay" (20 feet thick), with the lithologic intervals targeted by well screens totaling 320 feet in thickness. Bauer Well 2 (observation well) is screened across 410 to 500 feet, 520 to 580 feet, 640 to 700 feet, 790 to 850 feet, 870 to 910 feet, and 960 to 990 feet, totaling 340 feet of well screen. According to the drillers log, screened intervals in Well 2 are adjacent to fine- to coarse sand and gravel up to boulders. The screened intervals of both wells correspond with the older alluvium at this location in the valley.

Well 1 was pumped at an approximate constant rate of 2,300 gallons per minute (gpm) for a duration of 407 minutes (approximately 6.8 hours). Water levels were measured in Well 2 during pumping and recovery phases. A total of 1.08 feet of drawdown was measured in Well 2 during pumping at Well 1 (Figure 23). After about 60 minutes the water level response in Well 2 indicated delayed drainage, however, the duration of pumping was not long enough to evaluate specific yield. During recovery, the water level reached its approximate static level at a t/t' time value (time since pumping started/time since pumping stopped) of almost 5, indicating the influence of a recharge source to the aquifer during the test (Figure 24).

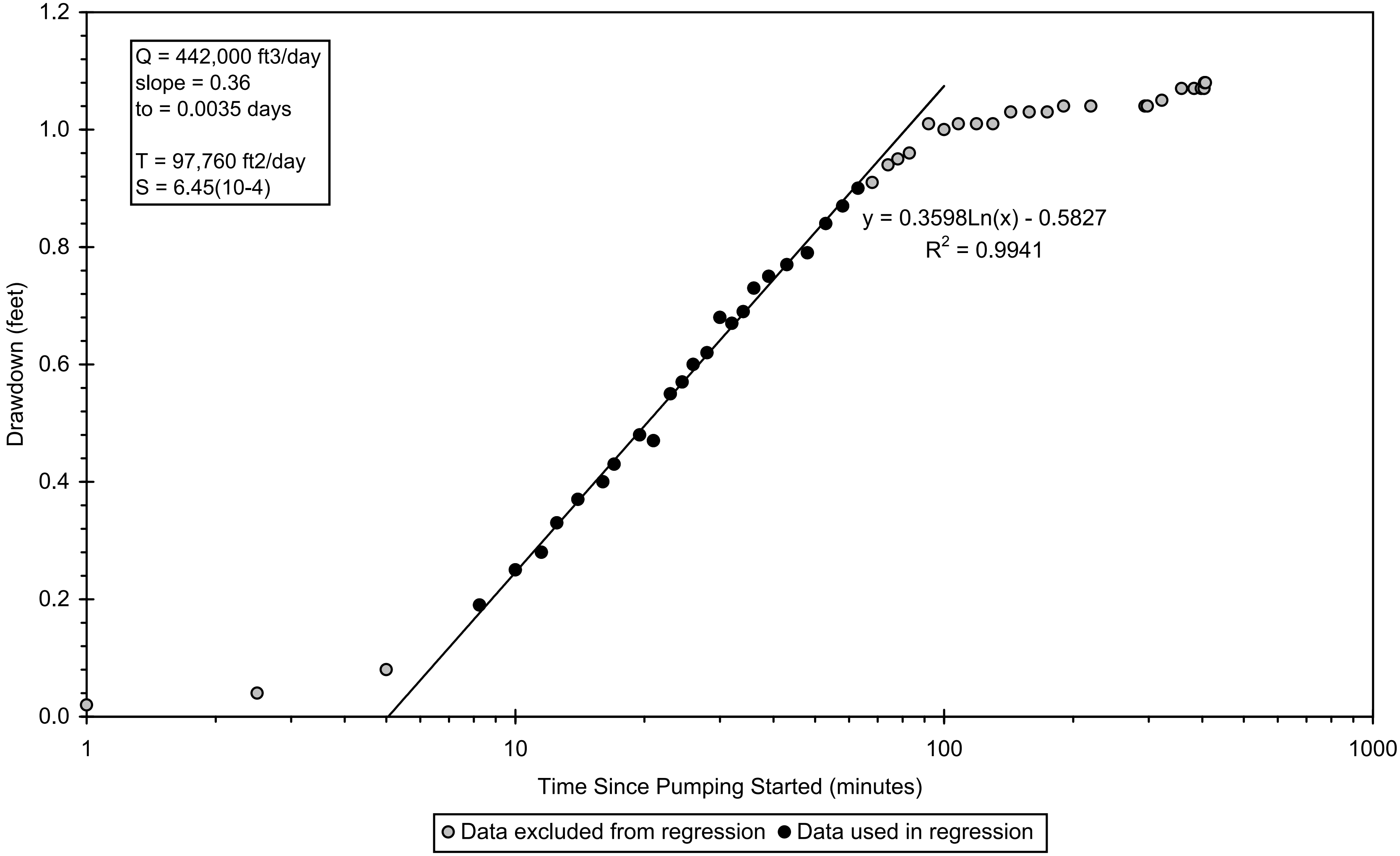


Figure 23. Drawdown in Bauer Well 2 due to Pumping at Bauer Well 1.

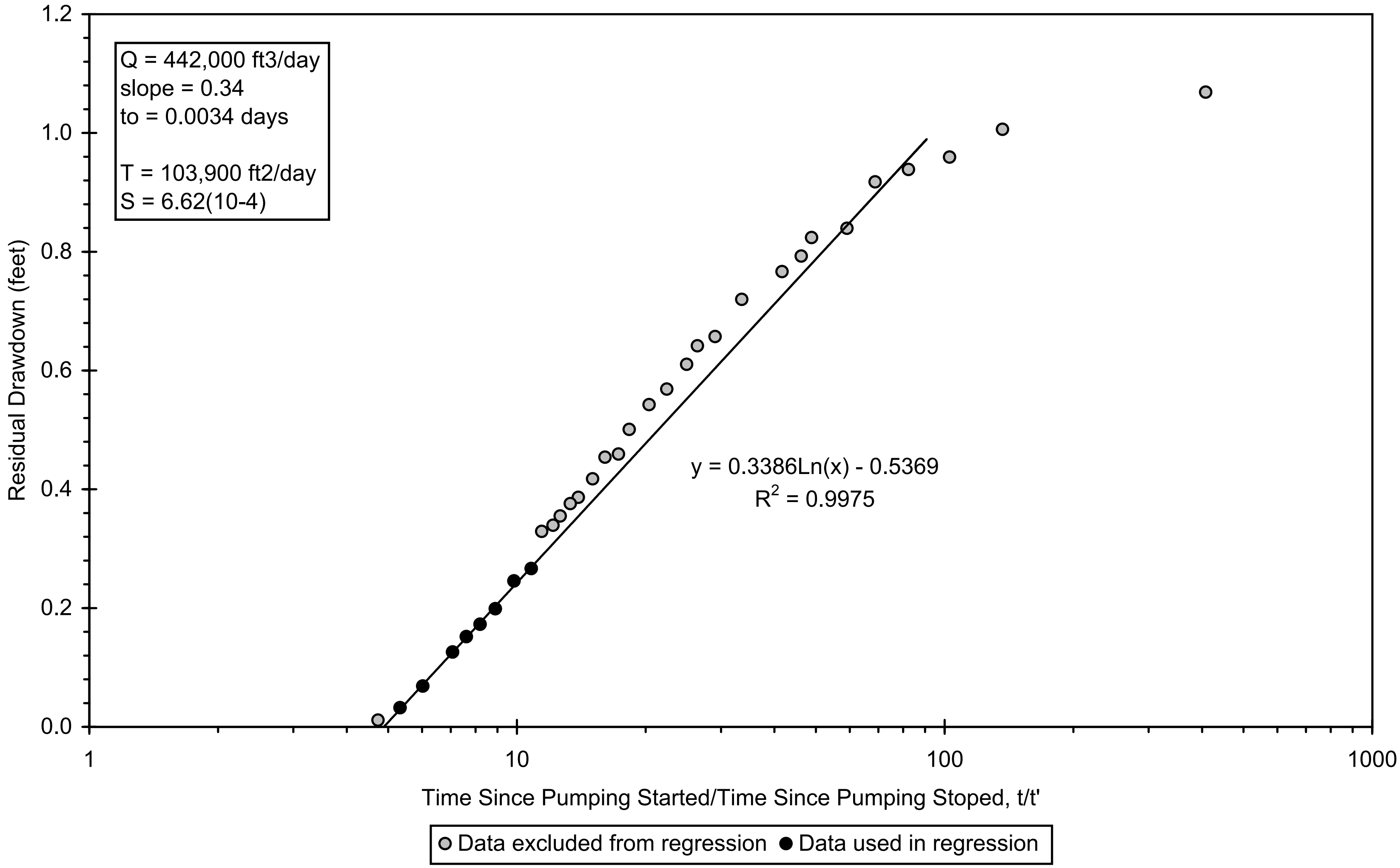


Figure 24. Residual Drawdown in Bauer Well 2 during Recovery of Bauer Well 1.

The pumping and recovery phases of the test were analyzed separately using the Jacob method (Cooper and Jacob, 1946). The Jacob method is based on a truncated infinite series approximation of the Theis solution to transient well hydraulics (Theis, 1935). According to the Jacob method, a plot of drawdown versus log time will approach a straight line, with the slope of the line proportional to the transmissivity of the aquifer, as long as the approximation to the Theis solution is valid, according to the following equation:

$$T = 2.3*Q / (4*\pi*\Delta s)$$

where:

T = aquifer transmissivity
Q = constant discharge rate of well
Δs = drawdown over one log cycle of time.

Or, if the slope is given in terms of natural log, as is the case in Figures 23 and 24, the Jacob equation reduces to:

$$T = Q / (4*\pi*slope) \quad (1)$$

where *slope* is simply the slope in the equation of the straight line given in terms of natural log. For the recovery test, the data were plotted as residual drawdown versus log t/t' and analyzed using the same equation. The validity of the Jacob approximation can be tested using the following equation:

$$u = r^2S / (4*T*t)$$

where:

u = $(\text{dimensionless time})^{-1}$
r = radial distance from pumped well to observation well
S= aquifer storage coefficient
t = time.

The Jacob method is a valid approximation to the Theis solution for any value of $u < 0.05$ (Driscoll, 1986). In this case, the value of *u* calculated was less than 0.05 for both the drawdown and recovery test results, indicating the Jacob approximation was valid for both the drawdown phase analyses and recovery analyses. Transmissivity was calculated using equation (1) above and ranged from approximately 97,760 feet-squared per day (ft^2/day) during the pumping phase of the test to approximately 103,880 ft^2/day during the recovery phase, averaging approximately 100,000 ft^2/day. Assuming that the effective saturated thickness of the aquifer is the total length of well screen in the pumped well, and using the relationship K = T/b where *K* is the hydraulic conductivity of the aquifer and *b* is the effective saturated thickness of the aquifer (Fetter, 1988), the average hydraulic conductivity of the aquifer in the vicinity of these two wells is approximately 336 feet per day. This value is within the range expected for coarse sand, and is assumed to represent the hydraulic conductivity of coarse sand throughout the alluvium in Borrego Valley (Freeze and Cherry, 1979; Fetter, 1988).

The elastic response component of the total unconfined aquifer storage coefficient was calculated for both the pumping and recovery phases of the test using the equation $S = 2.25*T*t_o / r^2$ (Cooper and Jacob, 1946). The elastic storage coefficient ranged from $6.45x10^{-4}$ during the pumping phase to $6.62x10^{-4}$ during the recovery phase, averaging approximately $6.5x10^{-4}$. These values are in the range expected for elastic response, but are not representative of specific yields of unconfined aquifers (Freeze and Cherry, 1979). The specific yield is expected to be several orders of magnitude greater than the elastic storage coefficient for an unconfined aquifer, and it is typically taken to be equal to the total unconfined storage coefficient (Fetter, 1988). Due to operational constraints regarding irrigation of the citrus orchard, the test could not be run long enough to measure specific yield. Given the distance between wells, the test would likely need to be run for a substantial period of time in order to measure the specific yield of the aquifer.

Borrego Springs Water Company Well 5

Borrego Springs Water Company Well 5 is located in the central portion of the basin in the vicinity of the Roadrunner Country Club (Figure 22). The well is used for municipal supply to the service area of the Borrego Springs Water Company. Permission was obtained from the water company to test this well. The discharge pipe from the well was equipped with a totalizing flowmeter for measuring flow rate and an inline valve to adjust the flow rate. The well had barely adequate access for a small wire line sounder to measure water levels. Measuring water levels manually at this well was problematic due to the sounder becoming contaminated with pump turbine oil. The well was constructed with an airline that runs to an unknown depth below the pumping water level. During the test, pressure on the airline was monitored as a crude second method of measuring drawdown. Well 5 is screened across 520 to 570 feet, and 590 to 640 feet below ground surface, totaling 100 feet of well screen. These depths correspond to the older alluvium at this location in the valley. According to the drillers log, the well screens are adjacent to gravel and interbedded clay and gravel.

The well was pumped initially without changing the valve setting on the discharge line from its normal operating position. However, since discharge was being diverted to ground surface near the well, rather than into the conveyance pipeline, the well was pumping against less head than usual. As such, the discharge rate was higher than usual for that well, resulting in excess drawdown. It appeared that the well would run dry early in the test. To avoid this, at 31 minutes into the test, the discharge rate was adjusted from approximately 250 gpm to approximately 190 gpm, and was held at that rate for remainder of the pumping period of the test. The pumping period lasted for 744 minutes (12.4 hours) followed by recovery. The recovery curve diverted from its trend at a t/t' time of approximately 18, and at a t/t' time of approximately 7.5 the recovery test was abandoned, due to the apparent influence of another pumping well, possibly at the Roadrunner Country Club. Residual drawdown data collected from the airline during recovery were unusable.

Drawdown data were corrected for the adjustment in flow rate using the computer program *STEP* (Huntley 1989). *STEP* applies a time correction to data collected at variable rate pump tests to compensate for the change in rate so that drawdown data collected while the well was pumping at different rates will approach the same line on a plot of s/Q versus log corrected time, where *s* is drawdown. This method of analysis, described by Birsoy and Summers (1980), is similar to the Jacob method, and limited to the same criteria for validity. The Birsoy and Summers method states that the slope of a straight line fit to a plot of s/Q versus step corrected time is proportional to the transmissivity according to the equations above.

Transmissivity was calculated using drawdown data measured manually and with the airline, in addition to recovery data up to the point where recovery was interrupted (Figures 25 through 27). The value of *u*, which is used to test the validity of the Jacob approximation, is less than 0.05 when calculated for test results from the pumped well, and use of late drawdown and late recovery data in a Jacob type aquifer test analysis is generally considered valid for single well tests, i.e. tests with observation only from the pumped well. Measured transmissivity values ranged from 884 ft^2/day to 2491 ft^2/day. Typically when there is disagreement between drawdown and recovery results from a single well test, the drawdown results are considered less reliable as drawdown measured in the well is influenced by the well efficiency, and transmissivity can be underestimated. However, in this case, none of the data are of especially high quality, and results were averaged by first averaging the results from the two data sets collected during the drawdown period and the resulting value was averaged with the result from the recovery phase of the

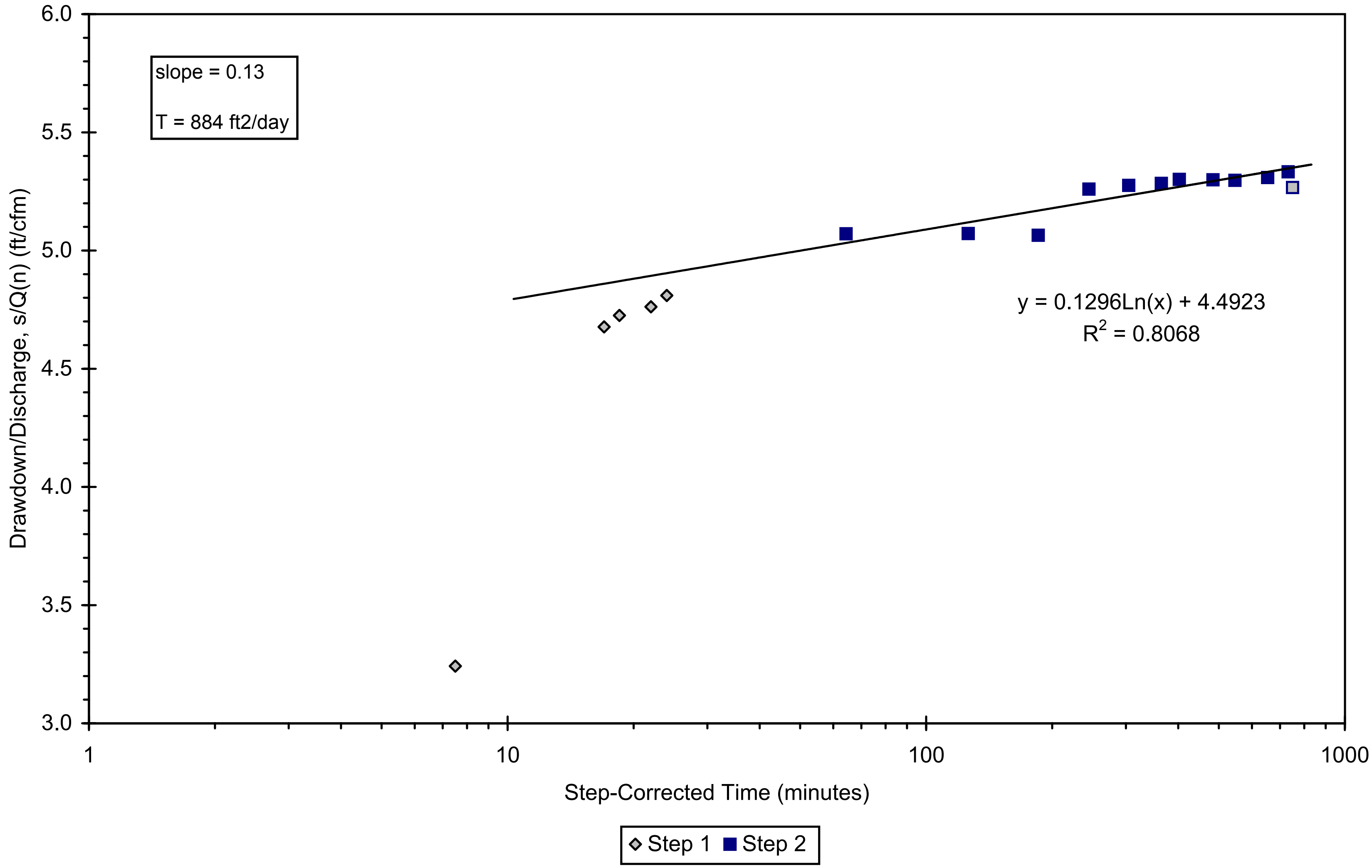


Figure 25. Stepped Drawdown During Pumping at Borrego Springs Water Company Well 5.

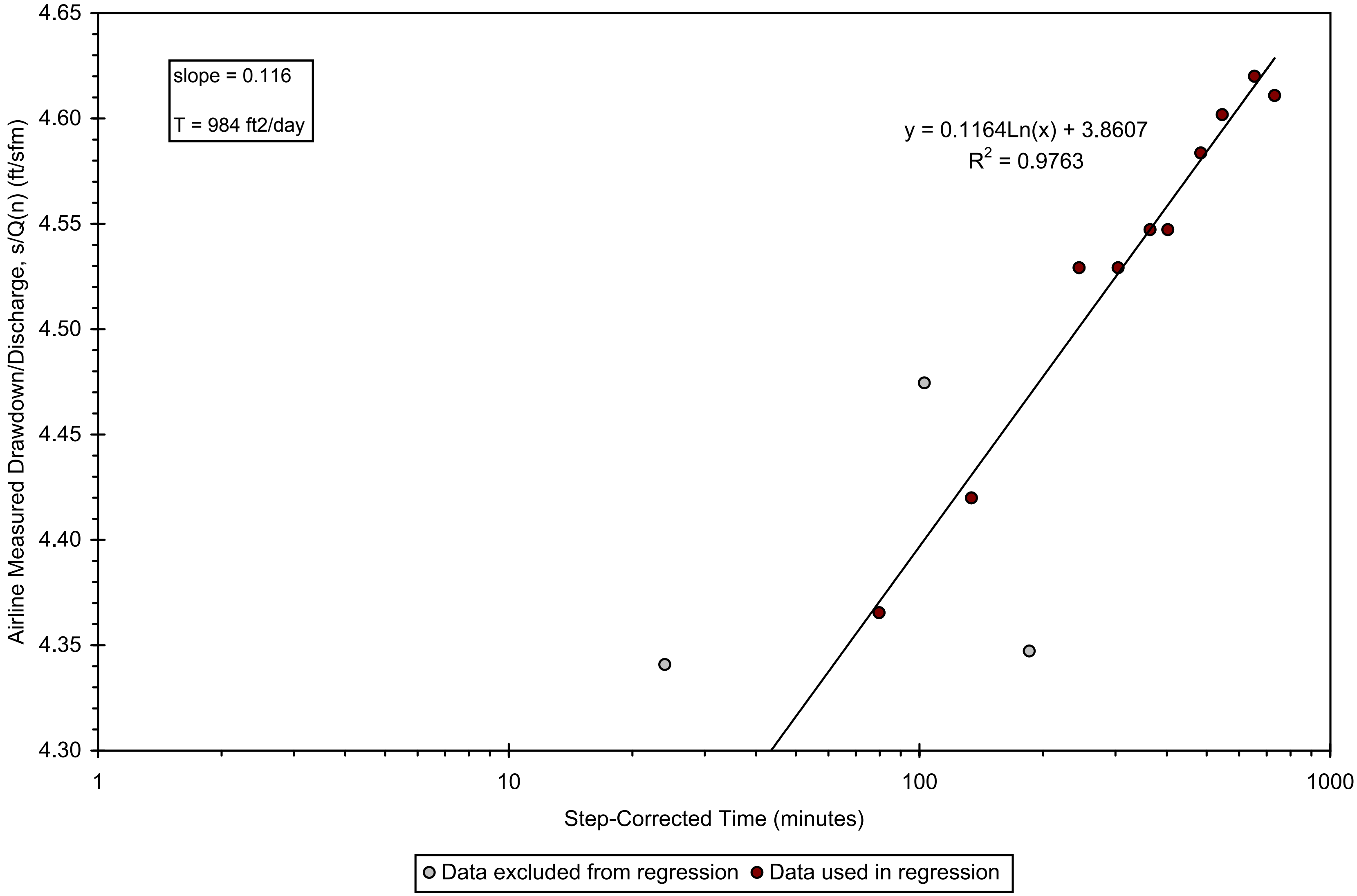


Figure 26. Airline Measured Stepped Drawdown During Pumping at Borrego Springs Water Company Well 5.

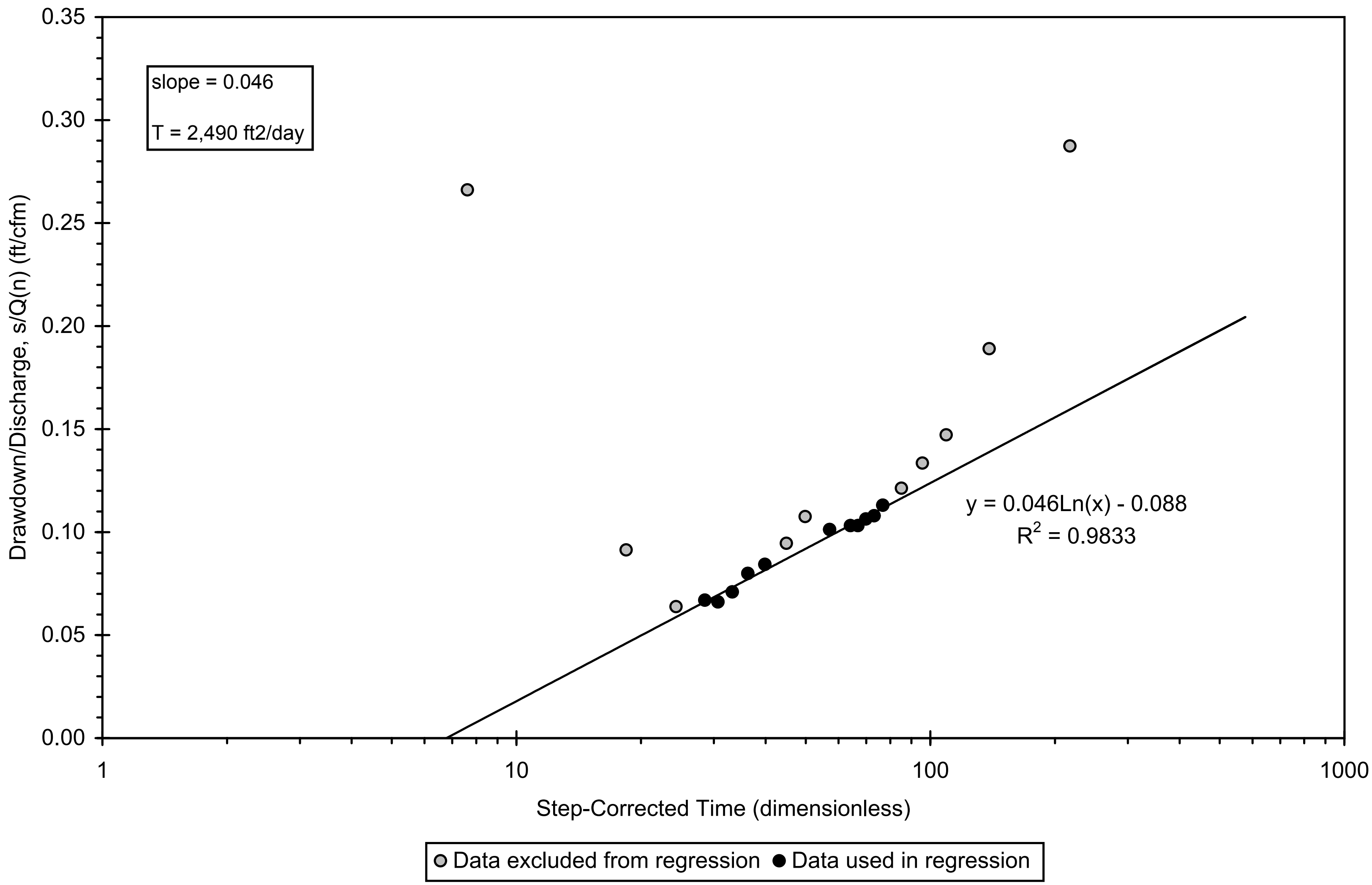


Figure 27. Residual Drawdown During Recovery from Stepped Pumping at Borrego Springs Water Company Well 5.

test. The resulting average transmissivity is approximately 1,700 ft^2/day. Assuming an effective saturated thickness of the aquifer of 100 feet (total screened interval), the average hydraulic conductivity at this location is approximately 17 feet per day. This value might be expected from a sequence of clay and gravel and is assumed to represent the interbedded clay and gravels found in the older alluvium in the area beneath the lacustrine deposits.

Borrego Water District Well 1

Borrego Water District Well 1 is located in southern Borrego Valley, southeast of Desert Lodge, and just to the west of where the Palm Spring Formation crops out (Figure 22). The well is used for municipal supply to the service area of the Borrego Water District. Permission was obtained from the water district to test this well. The discharge pipe from the well was equipped with a totalizing flowmeter for measuring flow rate and an inline valve to adjust the flow rate. The well was equipped with a 1-inch I.D. PVC chlorine injection tube that was accessed to use as a water level sounding tube during the test. Well 1 is screened across 180 to 230 feet, 240 to 456 feet, and 465 to 580 feet below ground surface, totaling 381 feet of well screen. This corresponds to what was interpolated as older alluvium. However, this portion of the alluvium is predominantly fine grained and was deposited in the trough of a localized syncline in the Sleepy Hollow folds. The materials on the driller's log are generally described as brown sandy clay and gray clay, with thinner sand and gravel interbeds.

The well was pumped at an approximate constant rate of 180 gpm for a duration of 734 minutes (12.2 hours). The well discharge was directed into the water district conveyance piping rather than to ground surface at the request of the Borrego Water District. At approximately 80 minutes into the test, an aquifer test at Borrego Water District Well 2 was started. However, there was a sudden drop in flow rate (and drawdown) at Well 1 as Well 2 was started due to increased pumping head in the Water District Pipeline (Figure 28). Upon recognizing this, the test at Well 2 was immediately abandoned and there were no significant detrimental effects to the overall test at Well 1 due to the brief pumping of Well 2. However, late in the pumping period the water district's water storage tank had filled to capacity and discharge was then diverted to ground surface near the well and the valve in the discharge piping was adjusted to match, as closely as possible, the flow rate prior to diversion of the discharge water. Nevertheless, the late drawdown fell off somewhat from the trend of the data curve. Recovery was monitored through a t/t' time of 2.35 (Figure 29).

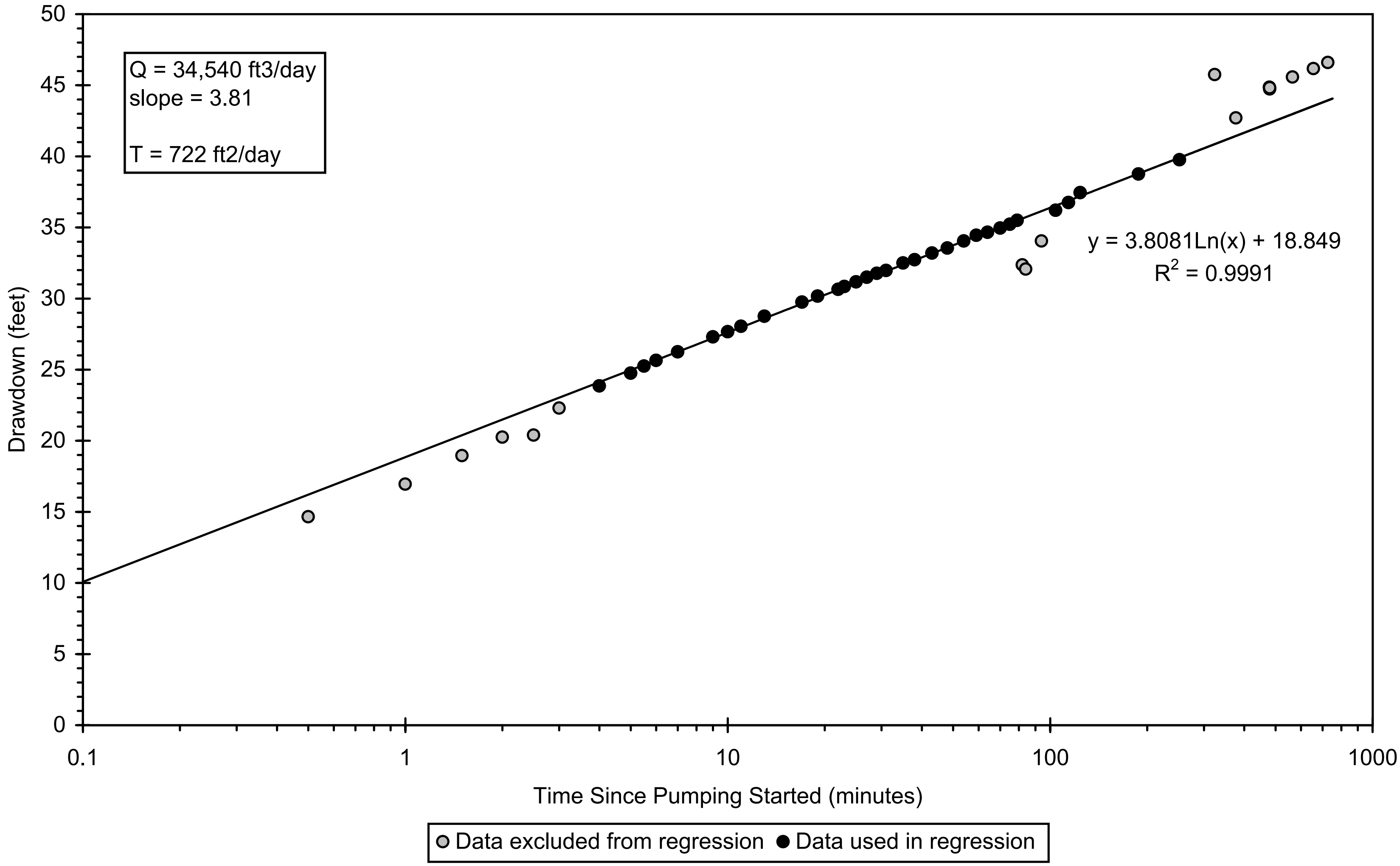


Figure 28. Drawdown During Pumping at Borrego Water District Well 1.

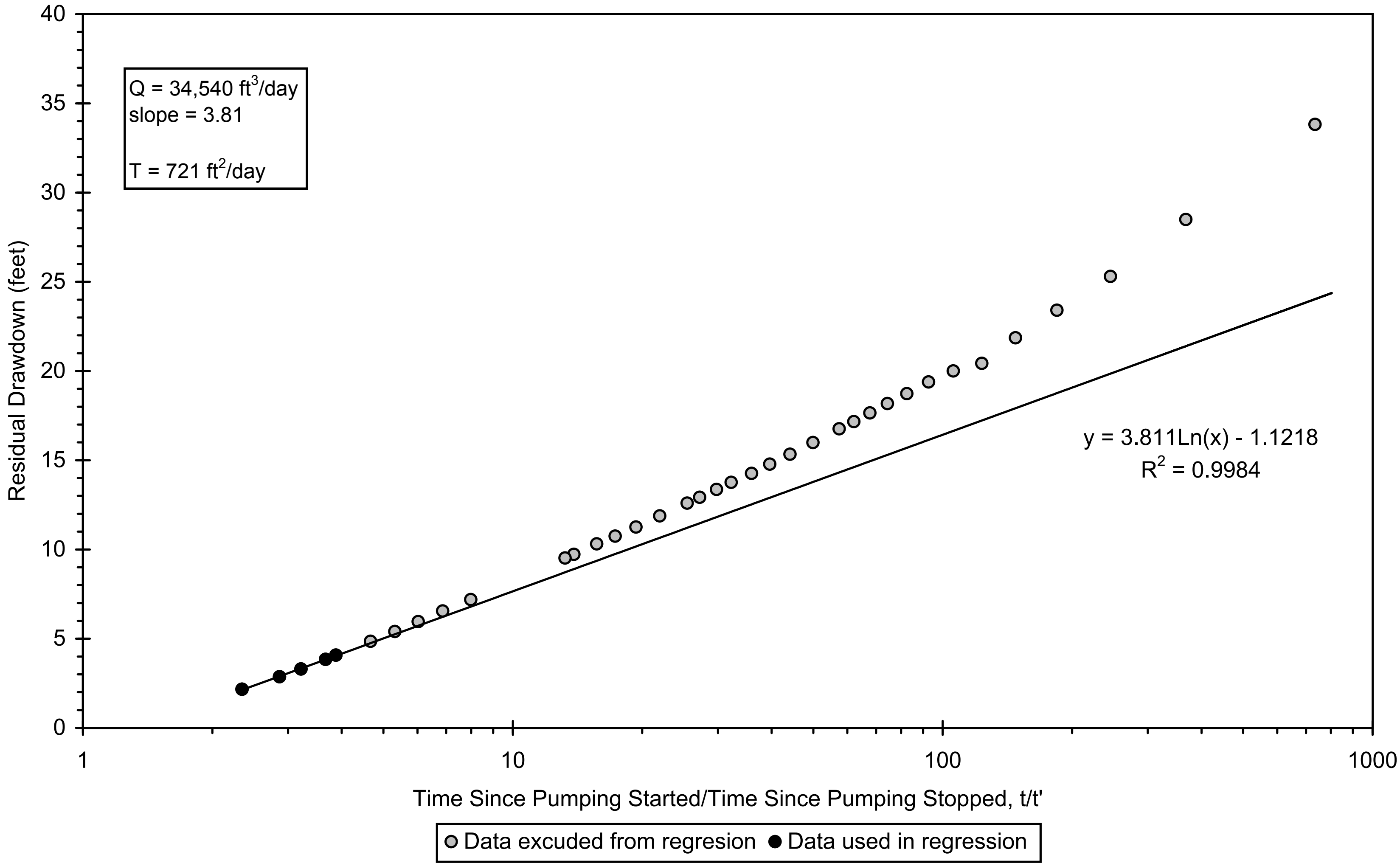


Figure 29. Residual Drawdown During Recovery at Borrego Water District Well 1.

Drawdown and recovery data were analyzed using the Jacob Method described above. Again, the value of *u* calculated for single wells tests is less than 0.05, and late drawdown and recovery data were considered valid for use in the analyses. There was excellent agreement between the results of the drawdown and recovery phases of the test, 722 ft^2/day and 721 ft^2/day, respectively. Assuming an effective saturated thickness equal to the total screened interval in the relationship K = T/b, the average hydraulic conductivity of the alluvial materials in the vicinity of this well is approximately 2 feet per day. This value is assumed to represent only the predominantly finer grained alluvial fill of the Sleepy Hollow syncline, while long-term groundwater flow to this area may be controlled by the hydraulic conductivity of the surrounding Palm Spring Formation (described below).

Borrego Water District Well 8

Borrego Water District Well 8 is also in southern Borrego Valley, not far from Well 1. The well is also used for municipal supply to the service area of the Borrego Water District. Permission was obtained from the water district to test this well. The discharge pipe from the well was equipped with a totalizing flowmeter for measuring flow rate and an inline valve to adjust the flow rate. The well had barely adequate access for a small wire line sounder to measure water levels. The well was constructed with an airline that runs to an unknown depth below the pumping water level. During the test, pressure on the airline was monitored as a crude second method of measuring drawdown. Well 8 is screened across 7 to 24 feet, 260 to 312 feet, and 312 to 830 feet below ground surface, totaling 738 feet of well screen. This well is interpreted to be completed almost entirely in the Palm Spring Formation, with a portion of the upper screen in the intermediate aged and older alluvium. The driller's log indicates predominantly red clay with fine to coarse sand interbeds.

The well was pumped at an approximate constant rate of 310 gpm for a duration of 508 minutes (8.5 hours). Recovery was monitored through a t/t' time of 2.5, when the well had attained full recovery to its static level. Drawdown data were unusable due to considerable pumping loss and a poor linear trend of drawdown versus log time. However, recovery data was well behaved and analyzed using the Jacob method described above (Figure 30). As with the other single wells tests, the late recovery data were considered valid for use in the analyses. The transmissivity measured at Well 8 was 8,366 ft^2/day. Assuming an effective saturated thickness equal to the total screened interval of the well, the average hydraulic conductivity of the Palm Spring Formation is approximately 10 feet per day. This is the only value of hydraulic conductivity measured for the Palm Spring

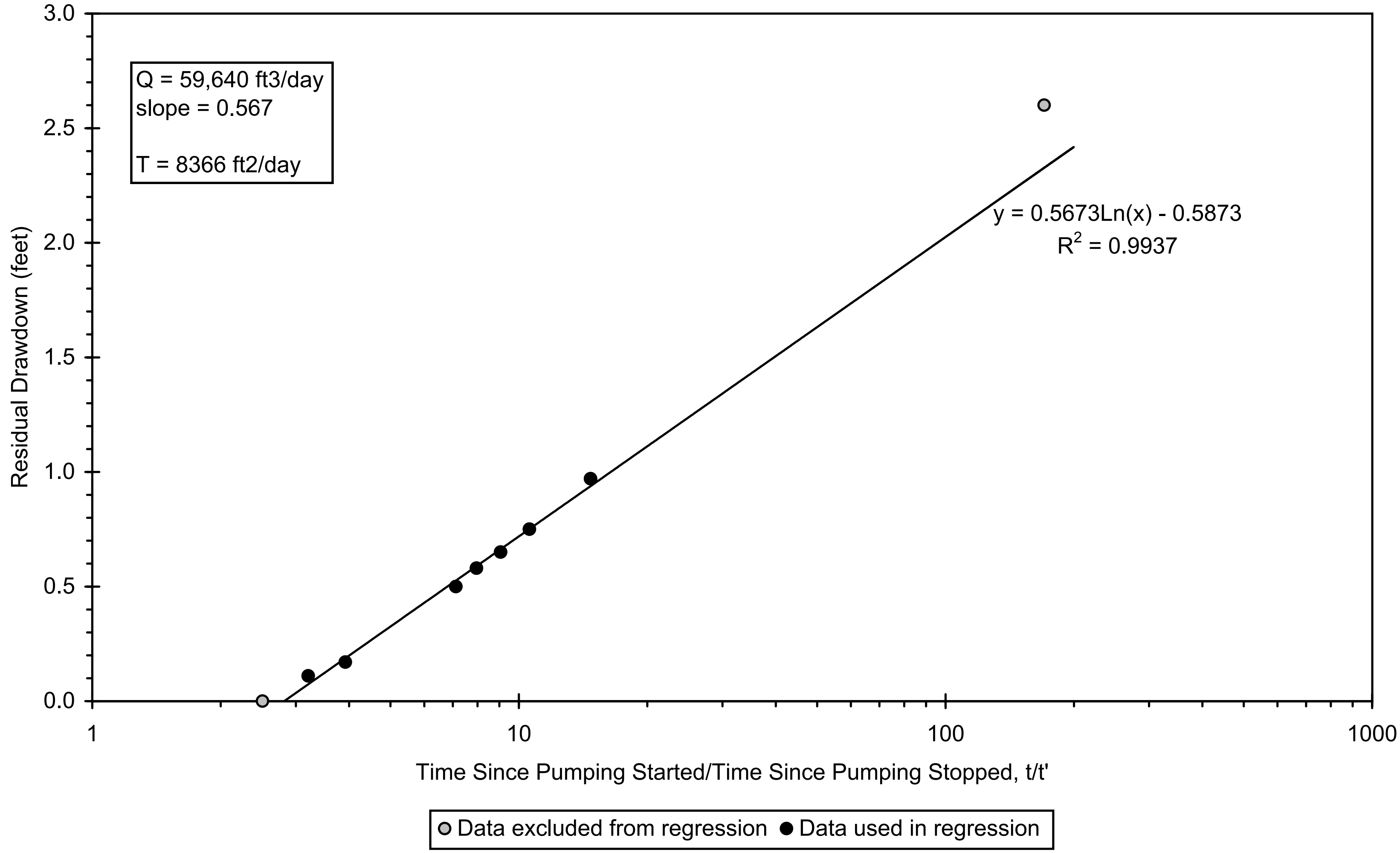


Figure 30. Residual Drawdown During Recovery at Borrego Water District Well 8.

Formation in Borrego Valley and it was assumed to represent the entire Palm Spring Formation in Borrego Valley.

Hydraulic Testing Summary

Hydraulic conductivity is a function of the grain size of a porous medium, specifically the size of the openings through which water flows. Resistance to flow is inversely proportional to the square of the mean pore diameter. The Hazen method describes a technique for estimating hydraulic conductivity from grain size distribution curves of sandy sediments using the equation $K = C(D_{10})^2$ where *C* is a coefficient that varies depending on the mean grain size and sorting of the sandy material, and D_{10} is the effective grain size (the grain diameter where 90 percent by weight of a sample is coarser) (Fetter, 1988). The method requires results from grain size analysis, specifically the mean and the effective grain diameter, and the degree of sorting or uniformity coefficient. This method is most beneficial in a situation where direct measurements of hydraulic conductivity are lacking, and grain size analyses have been performed. In Borrego Valley, only rough estimates of the mean grain size can be made based on lithologic descriptions on driller's logs, and the Hazen method cannot be directly applied. However, the principal of relating hydraulic conductivity to the square of the grain diameter was applied in a simplified way, by deriving an empirical relationship, analogous to *C* in the Hazen method, using measured hydraulic conductivity and the associated grain size described on the driller's log, as described below.

Four aquifer tests were performed to measure transmissivity in Borrego Valley. One test, in northern Borrego Valley representing the coarse sands of the older alluvium resulted with a transmissivity of 100,000 ft^2/day and a hydraulic conductivity of 340 feet per day. One test, in central Borrego Valley, completed in interbedded clay and gravel in the distal portion of the older alluvium toward the southern central portion of the valley, resulted in a transmissivity of 1,700 ft^2/day and a hydraulic conductivity of 17 feet per day. Two tests in southern Borrego Valley, one well completed in relatively fine distal portions of the older alluvial valley fill resulted in a transmissivity of 720 ft^2/day and a hydraulic conductivity of 2 feet per day. The other well tested in southern Borrego Valley was completed almost entirely in the Palm Spring Formation and resulted in a transmissivity of 8,400 ft^2/day and hydraulic conductivity of 10 feet per day.

Based on the results above, and on the distribution of texture within the hydrostratigraphic units as observed on driller's logs (Figures 19 through 21), interpretations of the distribution of hydraulic conductivity throughout Borrego Valley have been made

(Table 1). Soil texture within the alluvium was related to hydraulic conductivity using the aquifer test result of 336 feet per day, from what was described on the driller's log as coarse sand, and the grain diameter for coarse sand ranging from 0.5 to 2 millimeters (Leeder, 1982), with the principal that hydraulic conductivity is related to the square of the grain diameter, as described above. In this way, estimates of hydraulic conductivity for gravel, medium sand, fine sand and silt, and clay were made based on relative grain diameters and the aquifer test results for coarse sand (Table 1). Hydraulic conductivity at locations within hydrostratigraphic units that could not be characterized by a single representative grain size, for example, stratified sections of interbedded clay and gravel or clay with interbedded sand within the alluvium or Palm Spring Formation, were characterized based on aquifer test results from wells completed in those interbedded areas of the hydrostratigraphic units (Table 1). Also included in Table 1, for comparison, are values of hydraulic conductivity reported in the literature for the various soil textures. Hydraulic conductivity calculated using grain size relationships agree moderately well with values reported in the literature. Within hydrostratigraphic layers 1 through 3, the alluvium and lacustrine deposits, hydraulic conductivity is estimated to range from a fraction of a foot per day to over a thousand feet per day, corresponding to textures ranging from clay to gravel, respectively. This is in contrast with assumptions used in previous studies, for example, the entire alluvial fill in Borrego Valley, corresponding to the upper aquifer described by Moyle (1982), was uniformly assigned a hydraulic conductivity of 50 feet per day.

Aquifer tests that were performed in Borrego Valley were insufficient to measure specific yield of the sediments. The lack of any observation wells near pumping wells and pumping duration constraints prohibited measurement of specific yield at the aquifer tests that were performed. Values of specific yield for the various soil textures reported in the literature have been summarized (Table 1).

Groundwater Flow and Water Levels

In the 1982 USGS report, several water level contour maps were presented, the latest for 1980. Since then, water level data collection has been from only a few key wells, and there has not been the necessary data density to construct updated water level maps. All the groundwater contour maps presented by Moyle display the same general regional flow conditions, but after 1945, flow from recharge areas becomes interrupted by several deep pumping cones of depression (Moyle, 1982). For example, the water levels in

Table 1. Soil Textural Relation to Hydraulic Properties

SOIL TEXTURE	GRAIN SIZE[a] Udden-Wentworth Grain Size Scale Phi (ϕ)			GRAIN SIZE[a] Grain Diameter, d (millimeters)			HYDRAULIC CONDUCTIVITY, K (feet per day) Aquifer Test Results	HYDRAULIC CONDUCTIVITY, K (feet per day) Aquifer Test-Grain Diameter Relationship[b]			HYDRAULIC CONDUCTIVITY, K (feet per day) Reported Values in Literature[c]		SPECIFIC YIELD[c] (percent)
Alluvium	Low	Middle	High	Low	Middle	High		Low	Middle	High	Low	High	
Fine Gravel	-1	-1.5	-2	2.00	2.83	4.00		1,344	2,688	5,376	328	3280	22 - 25
Coarse Sand	1	0	-1	0.50	1.00	2.00	336	84	336	1,344	66	328	27
Medium Sand	2	1.5	1	0.25	0.35	0.50		21	42	84	16	66	26 - 28
Fine Sand/Coarse Silt	5	4	2	0.031	0.063	0.25		0.33	1.3	21	0.28	16	18 - 23
Fine Silt/Clay	14	8	5	6E-5	0.004	0.031		1E-6	0.005	0.33	3E-6	0.28	2 - 8
Interbeded Clay and Gravel							17						
Clay with Interbedded Sand							2						
Palm Spring Formation													
Clay with Interbedded Sand							10						

FOOTNOTES:

(a) Wentworth scale as presented by Leeder (1982).

(b) Calculated using the principal that hydraulic conductivity is proportional to the square of the grain diameter with aquifer test results for coarse sand, 336 feet per day, and the intermediate grain diameter of 1 millimeter for coarse sand. For example:

$K_{gravel} = (K_{coarse\ sand}) / (d_{coarse\ sand})^2 * (d_{gravel})^2$

(c) Reported in Fetter (1988), and/or Kruseman and de Ridder (1990).

Figure 31 show steady-state 1945 flow conditions prior to significant pumping in Borrego Valley, while water levels in Figure 32 indicate flow conditions as they were impacted by pumping in 1980. The following discussion is based on the steady-state (1945) flow field in Borrego Valley as presented by Moyle (1982).

Groundwater flow through Borrego Valley is primarily from the areas of recharge around the western perimeter of the basin toward the topographic low at Borrego Sink (Figure 31). Historically groundwater was at or near the surface in the Borrego Sink. Groundwater flow from the Borrego Sink area appears to travel east, probably across the Coyote Creek Fault and then southeastward along the northeast edge of Borrego Mountain, towards Ocotillo Wells, much as the San Felipe Creek runs. Groundwater flow in the vicinity of where San Felipe Creek enters the valley predominantly flows to the southeast, towards Ocotillo Wells (Figure 31). Thus, little recharge, if any, from San Felipe Creek is likely to recharge the principal areas of the aquifer in Borrego Valley.

All available groundwater level data for the Borrego Valley and vicinity were obtained from DWR, USGS and San Diego County databases. Water level data from all sources were compiled and water level hydrographs for each well were prepared (Figure 33; Appendix B). A few representative hydrographs are plotted in Figure 34. Some general trends are noted throughout most of the hydrographs for the valley. Water levels were typically declining from the early 1950's through about 1965. The representative wells in Figure 34 drew down approximately 20 to 40 feet during this time, though reports of drawdowns over 100 feet were reported. These latter reports were likely from wells in close proximity to pumping wells. During the period from approximately 1966 through the late 1970s, drawdown leveled off in most wells while some continued to draw down at lesser rates, and some even recovered a small amount. During the period from 1970 through the present, water levels in the majority of wells in Borrego Valley again declined, some at considerable rates. Based on recent water level monitoring in a few key wells, water level drawdown is currently ranging from just under a foot per year to 3.5 feet per year and averaging about 2 feet per year (Appendix B).

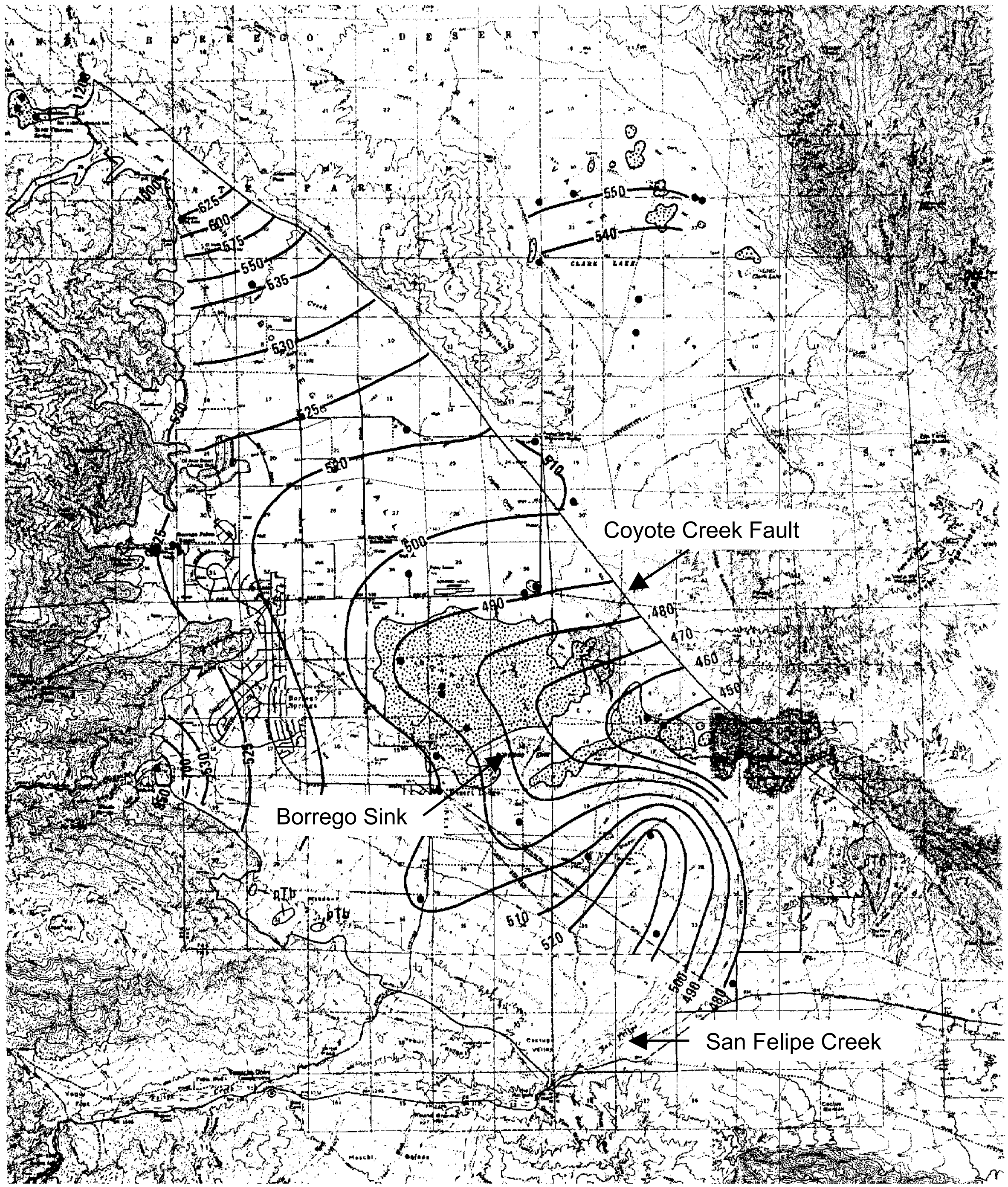
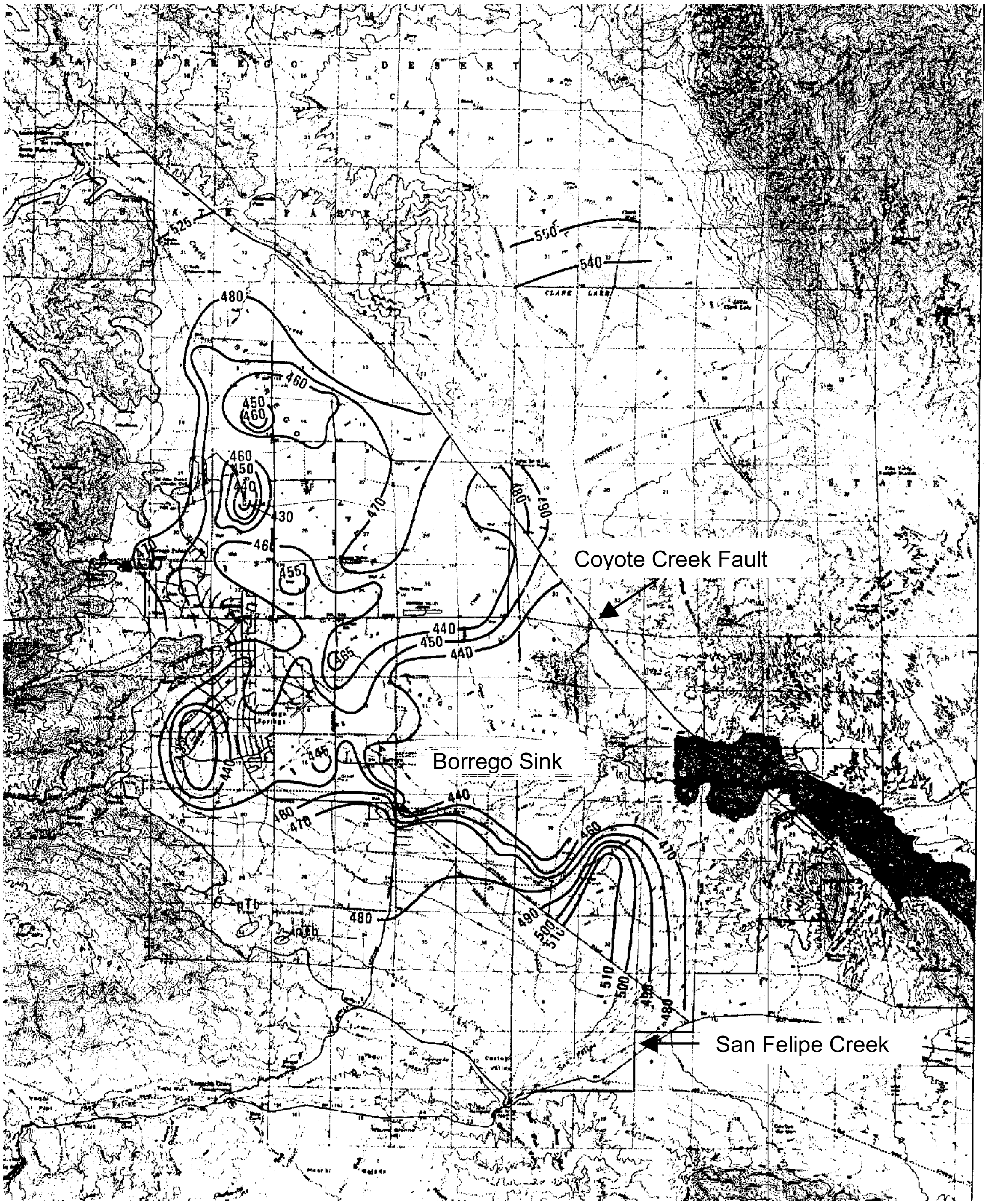


Figure 31. Steady State (1945) Water Level Elevation (feet mean sea level).



From Moyle (1982).

Figure 32. 1980 Water Level Elevation (feet mean sea level).

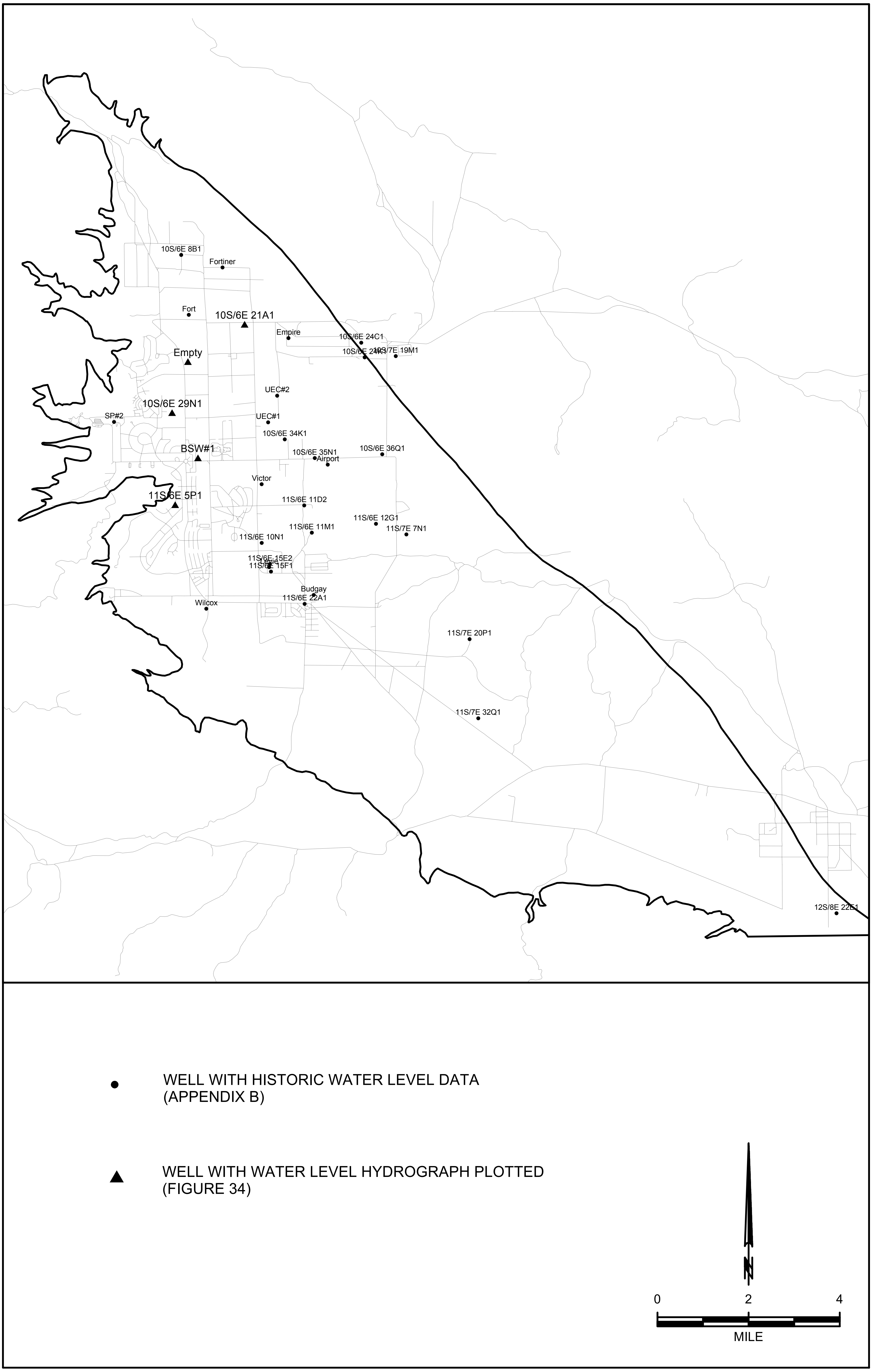


Figure 33. Location of Wells Where Water Level Data Have Been Collected - Borrego Valley.

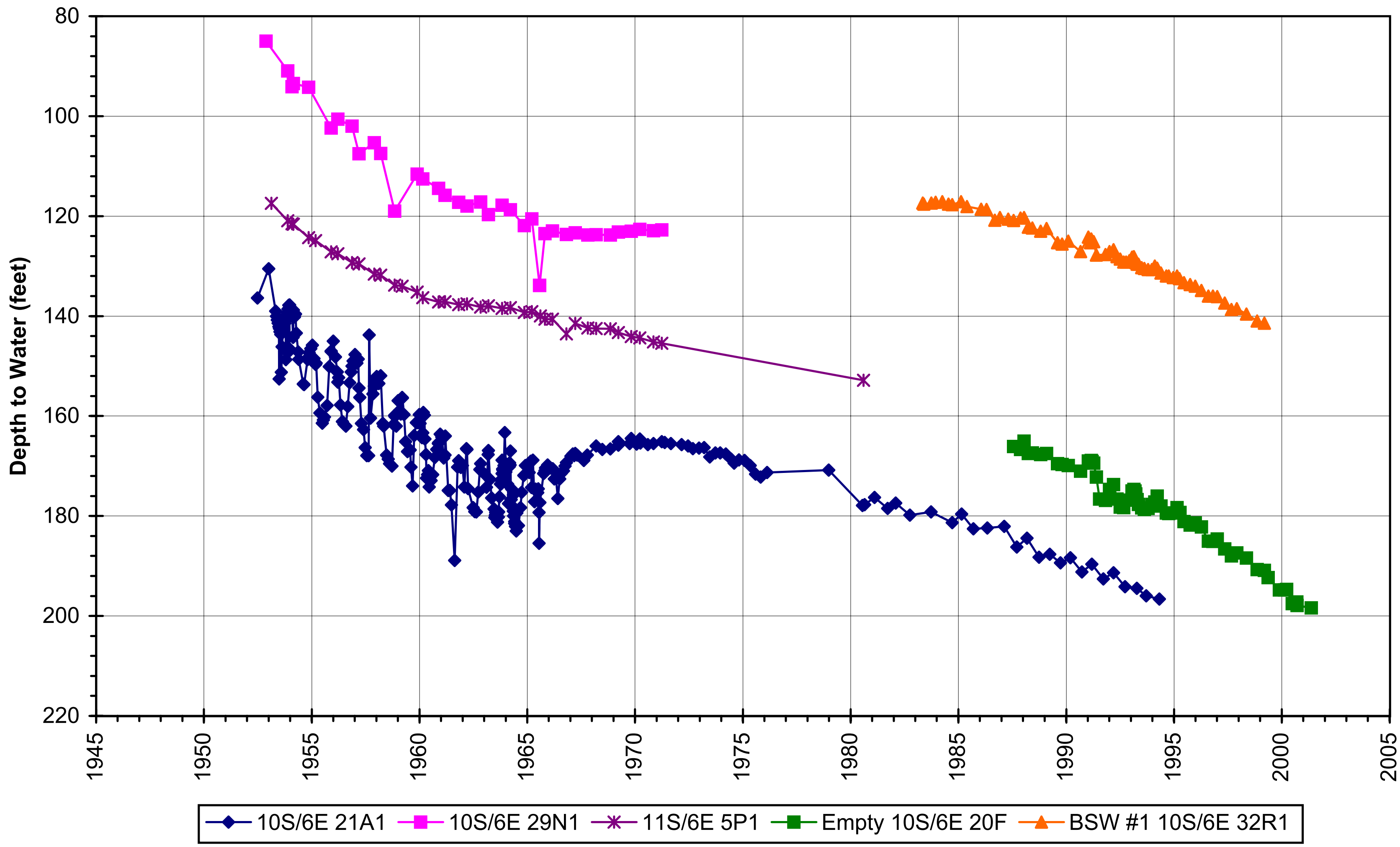


Figure 34. Historic Water Level Trends, Borrego Valley.

CHAPTER IV

WATER BUDGET

A groundwater budget was computed to estimate the net change in groundwater storage within the Borrego Valley aquifer system. Key components of the groundwater budget are recharge to and discharge from the aquifer system. Recharge to the aquifer system is comprised of all sources of water inflow to the groundwater basin, such as infiltration of surface water runoff, groundwater flow from adjacent basins, and irrigation return flow. Conversely, discharge from the aquifer system is comprised of all sources of water outflow from the groundwater basin, such as evapotranspiration, groundwater flow to adjacent basins, and groundwater production. The net change in groundwater storage is computed as the difference between the total recharge to, and the total discharge from, the aquifer system. Comparison of the net water budget with observed fluctuations of water levels in the aquifer system is demonstrative of the aquifer response to the varying stresses of recharge and discharge. An evaluation of recharge to and discharge from the groundwater basin is described in the following sections, and a comparison of the net water budget to observed water level response follows.

Sources of Recharge

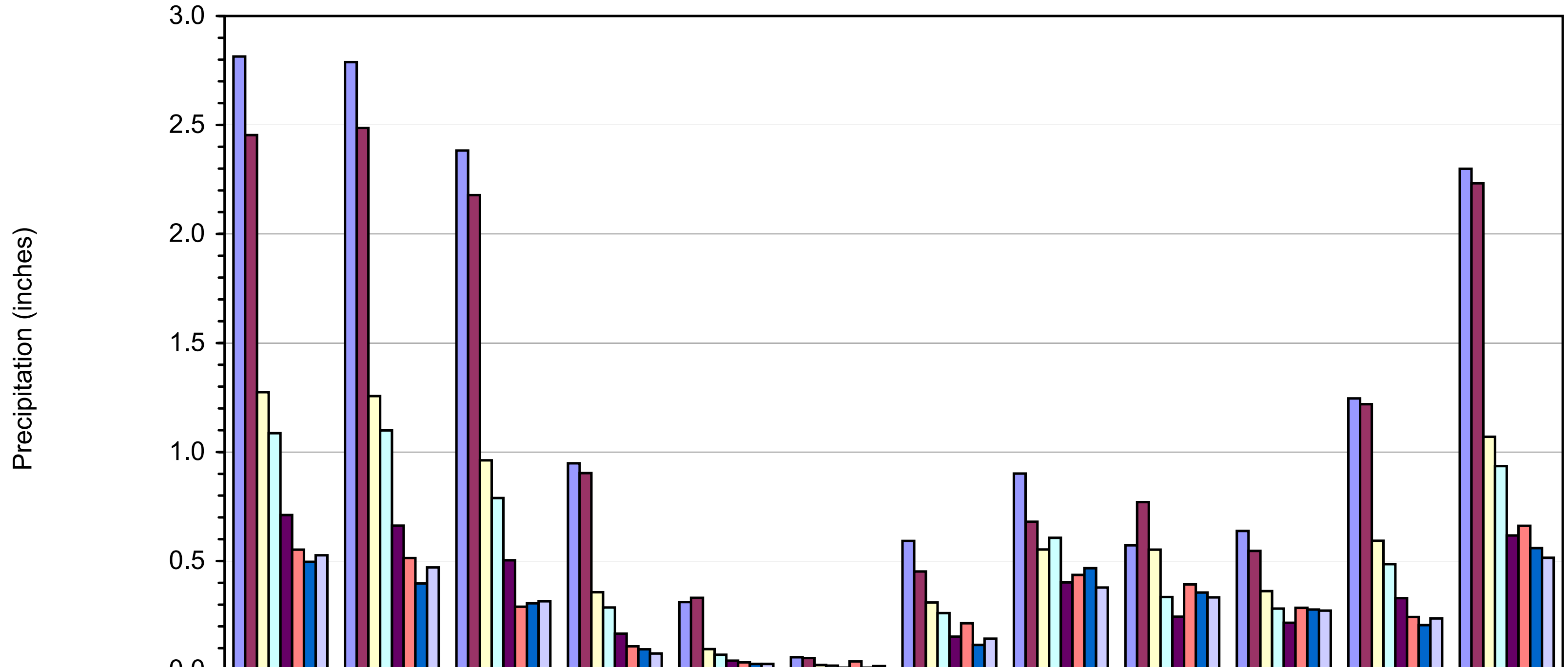
The ultimate source of recharge to groundwater in the Borrego Valley aquifer is precipitation. Precipitation over the surrounding watershed generates surface water runoff, primarily from the mountains that flank the basin to the north, west and south of Borrego Valley (Figure 3). Runoff from the surrounding mountains enters the valley along several creeks and intermittent streams and infiltrates into the ground at the heads of alluvial fans or along the streambeds as they run out into the valley. This is the primary source of recharge to the Borrego Valley Aquifer and is referred to in the remainder of this document as *stream recharge.*

A portion of the precipitation over the watershed infiltrates through the soil and into the underlying bedrock as groundwater recharge to the surrounding drainages. This groundwater then seeps through the surrounding bedrock toward Borrego Valley. Groundwater seeps from the bedrock into the alluvial aquifer of Borrego Valley below ground surface at the contact between the bedrock surface and the alluvial aquifer. This recharge to the aquifer, referred to in the remainder of this document as *bedrock recharge*, is difficult to quantify and has either not been considered, or overly simplified, in previous water budgets for the basin.

Infiltration of rain falling directly on the valley floor is not considered a significant source of groundwater recharge. Borrego Valley is located within the rain shadow of the Peninsular Ranges and has an arid climate with mean annual rainfall of 3.3 inches measured at Borrego Springs during the period from 1945 to 1966 (National Oceanic and Atmospheric Administration [NOAA], 2001). Average rainfall measured at Borrego Springs has a somewhat bimodal distribution throughout the year with an average of 2.5 inches of precipitation occurring during winter months (October through April), and 0.8 inches of precipitation occurring during summer months (May through September) (Figure 35). With an annual mean high temperature of 85°F in Borrego Springs (US Department of Agriculture [USDA], 1973), and mean annual potential evapotranspiration (PET) estimated for Borrego Valley of more than 70 inches (described below), average PET is several times greater than average precipitation throughout the entire year. Thus, recharge to groundwater occurring from infiltration of rain falling directly on the valley floor is expected to be minimal.

Another potential source of groundwater recharge to the Borrego Valley aquifer is underflow from adjacent basins. Groundwater flow through saturated alluvial sediments from adjacent basins or through alluvial filled channels entering Borrego Valley is referred to as *underflow*. Underflow along San Felipe Creek was estimated to be approximately 32 acre-feet per year (af/yr) (Moyle, 1982). Coyote Creek also has a relatively thick alluvial filled channel entering Borrego Valley. However, shallow bedrock and surface outcroppings near Santa Catarina Spring, upstream from the "Third-Crossing" of Coyote Creek, forces underflow through this channel to the surface and virtually all recharge from the Coyote Creek drainage enters the valley as surface water flow. Most other channels entering Borrego Valley contain very little alluvial sediments and underflow from these other channels is expected to be minimal (Moyle, 1982).

Irrigation return flow is another source of recharge that has either not been considered during previous water budgets or was overly simplified. Irrigation for agricultural land and golf courses are the most intensive uses of groundwater in Borrego Valley. Irrigation typically involves the over-application of water to prevent salts from accumulating in the soil. Water that penetrates the depth of root uptake and evaporation continues to



	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ranchita	2.81	2.79	2.38	0.95	0.31	0.06	0.59	0.90	0.57	0.64	1.25	2.30
Anza	2.45	2.49	2.18	0.90	0.33	0.06	0.45	0.68	0.77	0.55	1.22	2.23
Coyote Canyon	1.27	1.26	0.96	0.36	0.10	0.02	0.31	0.55	0.55	0.36	0.59	1.07
Borrego Park	1.09	1.10	0.79	0.29	0.07	0.02	0.26	0.61	0.33	0.28	0.49	0.94
Borrego Springs	0.71	0.66	0.50	0.17	0.04	0.01	0.15	0.40	0.24	0.22	0.33	0.62
Ocotillo 2	0.55	0.51	0.29	0.11	0.03	0.04	0.21	0.44	0.39	0.29	0.24	0.66
Coyote Wells	0.50	0.40	0.31	0.09	0.03	0.01	0.12	0.47	0.36	0.28	0.21	0.56
Ocotillo Wells	0.53	0.47	0.32	0.08	0.03	0.02	0.14	0.38	0.33	0.27	0.24	0.51

Figure 35. Monthly Mean Precipitation, Based on Estimated and Reported Values, Borrego Valley and Vicinity, California.

infiltrate down and returns to groundwater as recharge. Irrigation efficiencies have been estimated and irrigation return flow is accounted for in water budget calculations in terms of a net groundwater extraction for irrigation (discussed later).

Estimates of recharge to the Borrego Valley aquifer during the period 1945 through 2000 were calculated by evaluating these discrete sources of recharge. Recharge was calculated from 1945 as the beginning of the transient period of groundwater development in Borrego Valley. Prior to 1945, few wells were drilled in Borrego Valley and pumping of groundwater was minimal. To the extent possible, historically observed and reported data have been used in the calculations of recharge. Where data were lacking, empirical and/or analytical relationships have been utilized to estimate missing records during this period. Precipitation in the vicinity of the Borrego watershed during this period was evaluated, as precipitation is the direct source of stream and bedrock recharge and indirectly the source of all other recharge to the Borrego Valley aquifer. Estimates of stream and bedrock recharge, as well as an evaluation of irrigation return flow, follow the discussion of precipitation in the following sections.

Precipitation

Precipitation over the Borrego watershed was estimated on a monthly basis for the period 1945 through 2000. Monthly estimates of precipitation in each of the 15 discrete sub-drainage basins of the watershed were required to evaluate rainfall-runoff relationships for stream recharge and for the bedrock recharge analysis. The estimation of monthly precipitation in each sub-basin of the Borrego watershed during the period 1945 through 2000 was a two-step process. *First*, precipitation data were evaluated from eight representative precipitation stations in the vicinity of the Borrego watershed. All of the stations in the vicinity of the Borrego watershed had incomplete or missing records during the period 1945 through 2000, which complicated the analysis. Estimates of missing precipitation records were made using results from double-mass analyses for each station. The double-mass analysis is commonly used in hydrologic studies to test the consistency of various hydrologic measurements and to estimate missing records (Linsley et al., 1958; Searcy and Hardison, 1960). *Second*, after a “complete” record of reported or estimated monthly precipitation was compiled for each station, an empirical precipitation-elevation relationship was developed to interpolate monthly precipitation in each of the sub-basins. The double-mass precipitation analysis and precipitation-elevation interpolations for the individual sub-basins are described in the following sections.

Double-mass precipitation analysis. Consistent with the double mass theory, a plot of cumulative precipitation measured at one station versus the cumulative precipitation measured at another during the same period should result in a straight line, as long as the data are proportional, with the slope of the line equal to the constant of proportionality between the two stations. A plot of the cumulation of one quantity versus the cumulation of another during the same time period is known as a double-mass curve. Double-mass curves can be used to check the consistency of precipitation measurements, and to estimate missing precipitation records (Linsley et al., 1958; Searcy and Hardison, 1960). Consistency of precipitation measurements at a station can be checked by plotting a double-mass curve against other nearby stations. Any break in the slope of the line represents an inconsistency in the measurement record at one of the stations, and by plotting a double-mass curve for each station against several other nearby stations, inconsistencies at individual stations can be identified. Care should be taken, however, when plotting double-mass curves in an area such as the Borrego watershed, where there are substantial elevation and climatic change through the study area. In this case, only stations that were nearby and/or were in the same climatic zone were evaluated together in double-mass plots. Inconsistencies identified in this way are usually the result of some change in the precipitation station. For example, the station may have been moved a short distance or an older gauge may have been replaced with a newer one. Of the stations used in the analysis of precipitation in the Borrego watershed, some of the inconsistencies were related to the periodic movement of some of the stations a short distance to new locations, but the change was not enough to meet the criteria of the National Weather Service (NWS) protocol to change the stations identification (Linsley et al., 1958). While every inconsistency, observed as a break in the slope of the double-mass plot, was not investigated, the change in the relationship between any two stations was accounted for while estimating missing records as described below.

Eight precipitation stations were identified within or near the Borrego watershed boundary. These stations are distributed at various elevations and are located within the different climatic zones within the watershed. Precipitation measured at these eight stations is considered representative of precipitation throughout the watershed. Data from these stations and many others that were used in the double mass analysis were obtained from NOAA and from the County of San Diego, Department of Public Works. The stations used to estimate precipitation throughout the watershed are listed here in alphabetical order of the NOAA/NWS Cooperative Station Name:

1. Anza,
2. Borrego Desert Park,
3. Borrego Springs 3 NNE (which is the comprehensive record for the older station named Borrego Springs and for this new station established a short distance away),
4. Coyote Canyon,
5. Coyote Wells,
6. Ocotillo,
7. Ocotillo 2, and
8. Ranchita.

None of these stations has a complete record of monthly precipitation during the period from 1945 through 2000; therefore the double-mass analyses was performed to estimate complete monthly records for each of these stations. Data from these eight stations, as well as several additional stations in the general vicinity of and/or in the same climatic zone as each of these stations were used in the double-mass analysis to estimate missing records (Appendix C).

The NWS method for estimating missing precipitation records is to average either weighted or un-weighted (depending on the variability of precipitation between stations) records for three nearby stations around the station with the missing record. In this study, a more sophisticated approach was taken to estimate missing precipitation data, though reportedly no more accurate than the NWS method (Searcy and Hardison, 1960). A double-mass curve was plotted for each of the eight stations listed above against at least six other stations nearby or in the same climatic zone (Appendix C). The periods of record for the station missing data, and for the six or more surrounding stations, unavoidably varied and overlapped as no individual record was complete. In each case, the cumulative mass was plotted during the period when records existed for both stations. In this way the constants of proportionality (slope) between each of the eight stations listed above and each of the six or more surrounding stations were determined. In some cases an inconsistency in the record was indicated by a break in the slope of the double-mass curve, resulting in two separate slopes that apply to specific periods in their records (Appendix C).

For each of the eight stations listed above, the following method was used to estimate missing monthly precipitation records. For any given missing record, an estimated record was calculated by multiplying the precipitation measured at the adjacent station during that month by the slope of the double-mass curve between the two stations. Slope of the double mass curves ranged from approximately 0.2 to 5.6. In most cases, when one of the stations was missing a record, more than one of the surrounding stations had a concurrent measurement. In these cases, estimated records were calculated based on each of the surrounding stations with a concurrent measurement. The resulting estimates were then weighted by the inverse of the distance between that station and the station missing the record. In this manner, inverse distance weighted double-mass estimates were used to complete the monthly record for each of the eight stations listed above during the period 1945 through 1997 (Appendix C).

Verifications of the results of this analysis were made by plotting, for each of eight stations listed above, the difference between reported and calculated monthly precipitation (Appendix C). In all cases the vast majority of estimates are very close to measured values. However, in all cases there are several scattered outliers where the calculated precipitation does not agree very well with the reported value. This may be due to instances when high precipitation is observed at one station while it did not rain much at an adjacent station during the same period. While this may be related to the random nature of summer thunderstorms, it may also be an indication that other factors are influencing the distribution pattern of precipitation. Nonetheless, given that the vast majority of estimates agree very well with observed precipitation, the estimates made in this analysis are considered representative for the missing records at the stations.

Monthly mean precipitation based on the complete records of estimated and reported precipitation was plotted (Figure 35). Comparison of this plot with the plot of monthly mean precipitation based on reported data alone (Figure 4) indicates a similar distribution of precipitation throughout the year. A point to note while comparing Figures 4 and 35 is that the monthly mean precipitation based only on reported data is often less than that based on an estimated complete long term record. Some of the stations with shorter periods of record may coincide with periods that were typically drier than the long term estimated averages. The precipitation stations in Figure 35 are listed in order of descending elevation. Inspection of this figure reveals a trend of increasing precipitation with increasing elevation. This relationship becomes more apparent when average annual precipitation at each of the eight stations is considered (Figure 36). The precipitation stations in Figure 36 are listed in order of increasing elevation. This relationship will be evaluated further in the next section.

Precipitation over the watershed. Monthly precipitation in each of the sub-basins of the Borrego watershed was estimated for the period 1945 through 2000 by interpolating between, or extrapolating from, precipitation measured at the precipitation stations discussed above. Moderately good correlation exists exist between average annual precipitation versus elevation at the precipitation stations (correlation coefficient [R^2]=0.96),

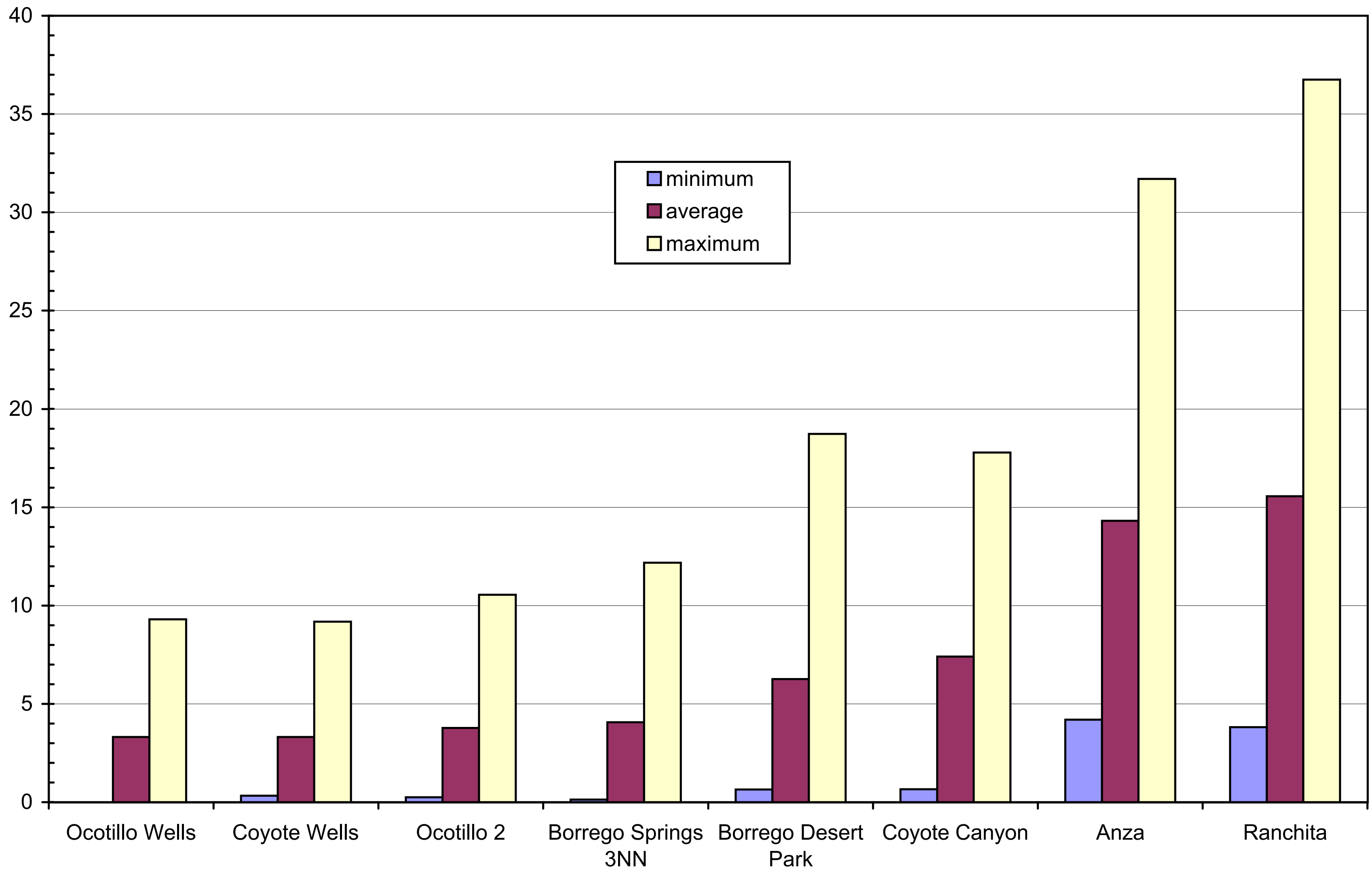


Figure 36. Annual Precipitation, Borrego Valley and Vicinity, California.

indicating elevation can be used, with some degree of confidence, to estimate precipitation in each of the sub-basins (Figure 37).

The area weighted average elevation was calculated for each of the fifteen sub-basins that drain into Borrego Valley and for Borrego Valley itself. United States Geological Survey (USGS) digital elevation model (DEM) data were used to calculate the area weighted average elevation for each sub-basin. USGS DEMs contain ground surface elevation data spaced on a regular grid, with each data point representing the elevation at the grid node. Area weighted average elevation for each sub-basin was determined by taking the subset of all DEM data nodes that were located within each basin. Since every data point in the DEM grid represents the elevation of an equal area, the average elevation in each sub-basins subset of DEM data is the area weighted average elevation for each sub-basin. The area weighted average elevation is more representative than a simple arithmetic average of the minimum and maximum elevation in a basin, in that it represents the elevation at which there is an equal area of the basin above and below the area weighted average elevation. Area weighted average elevation is referred to in the remainder of this document simply as *average elevation*. Sub-basin map areas were also compiled using USGS DEM data. The number of DEM data points that are located within each sub-basin was multiplied by the representative area of each data point (the DEM node spacing squared). In some cases the USGS DEM was re-grid using a smaller node spacing to provide better resolution.

Sub-basin map areas range from South Borrego Palm Canyon, at approximately 600 acres, to Coyote Creek, at approximately 97,500 acres (Table 2). Borrego Valley has an area of approximately 71, 700 acres (Table 2). Sub-basin average elevations range from East San Felipe Creek (approximately 1,500 feet above mean sea level [msl]), to Borrego Palm Canyon (approximately 4,500 feet msl). Borrego Valley has an average elevation of approximately 750 feet, though most of the developed portions of the valley occur at elevations between about 500 and 700 feet msl (Figure 2).

Monthly precipitation in each sub-basin was estimated by linearly interpolating between or extrapolating from monthly precipitation values for the stations nearest in elevation to the average elevation of each sub-basin. For example, in February 1980, the precipitation station at Coyote Canyon is estimated to have received 7.12 inches based on the double mass analysis described above, while the precipitation station at Anza recorded 11.39 inches (Appendix C). The station at Coyote Creek was located at an elevation of

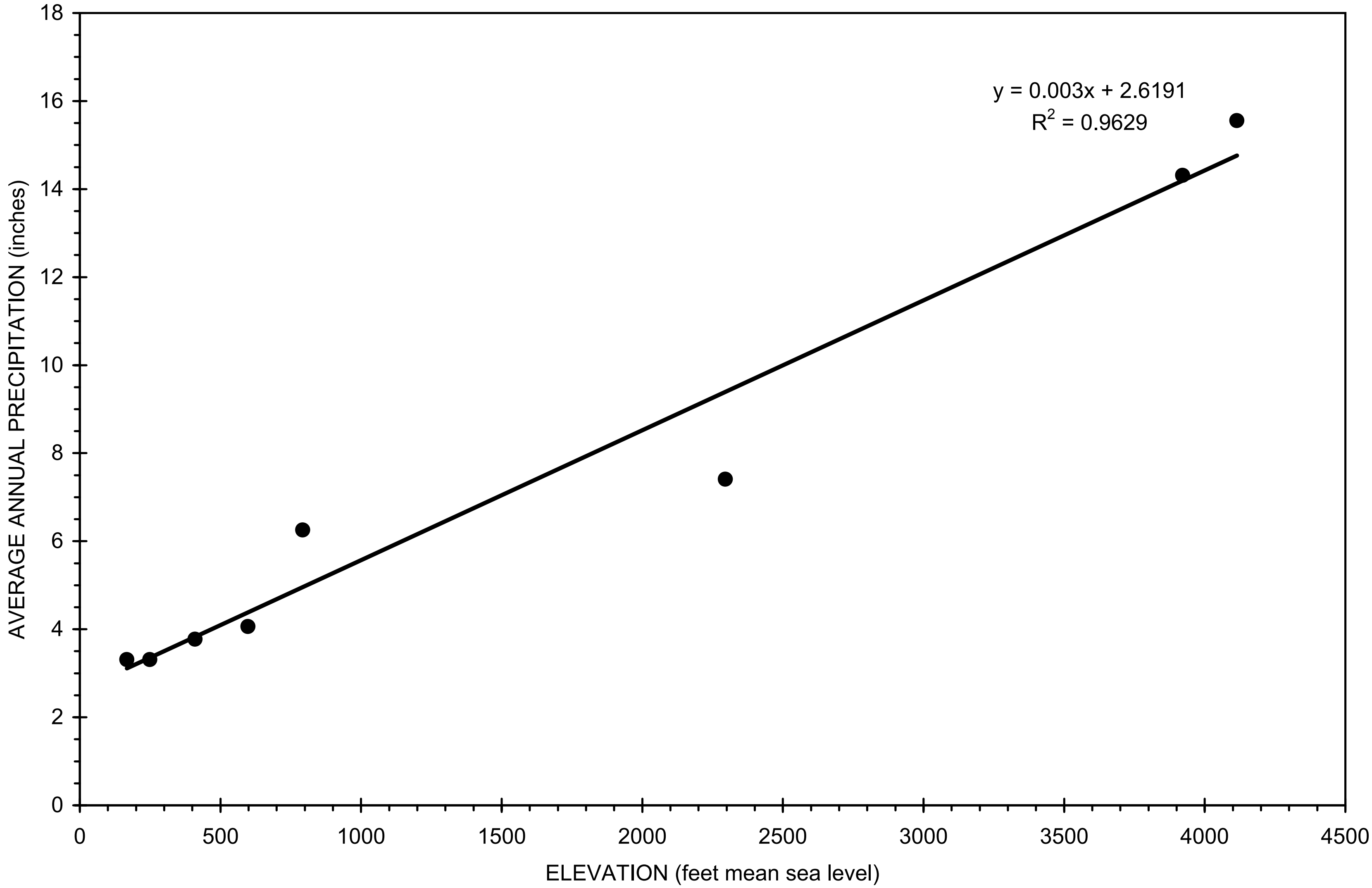


Figure 37. Average Annual Precipitation versus Elevation.

Table 2. Sub-Basin Elevation-Precipitation Summary

SUB-BASIN	SUB-BASIN AREA (acres)	AREA WEIGHTED AVERAGE ELEVATION (feet mean sea level)	ESTIMATED AVERAGE ANNUAL PRECIPITATION (inches)	ESTIMATED AVERAGE ANNUAL PRECIPITATION (acre-feet)
BORREGO VALLEY	71,670	756	5.84	34,875
EAST SAN FELIPE CREEK	1,289	1,528	6.82	732
COYOTE MOUNTAIN	4,504	1,529	6.82	2,559
INDIAN HEAD MOUNTAIN	965	1,884	7.09	570
NORTHWEST SLOPES	2,435	1,921	7.12	1,445
SOUTH COYOTE CANYON	2,532	2,241	7.37	1,554
DRY CANYON	1,524	2,245	7.37	936
LOWER SAN FELIPE CREEK	49,936	2,583	8.63	35,895
PINYON RIDGE	5,904	2,645	8.89	4,374
HENDERSON CANYON	3,743	2,786	9.49	2,959
SOUTH BORREGO PALM CANYON	579	2,801	9.55	461
UPPER SAN FELIPE CREEK	64,759	3,300	11.67	62,971
CULP-TUBB CANYONS	7,930	3,465	12.37	8,174
HELLHOLE CANYON	7,950	3,556	12.76	8,450
COYOTE CREEK	97,537	3,847	13.99	113,715
BORREGO PALM CANYON	13,819	4,514	17.37	20,008

2,296 feet msl while the station at Anza was located at an elevation of 3,922 feet msl. Monthly precipitation at sub-basins with average elevations between 2,296 feet msl and 3,922 feet msl were estimated by interpolating between the precipitation at these two stations. For instance, the Hellhole Canyon sub-basin has an average elevation of 3,556 feet msl. The monthly precipitation over Hellhole Canyon in February 1980 was estimated by interpolating linearly between 7.12 inches of precipitation at an elevation of 2,296 feet msl (at Coyote Canyon) and 11.39 inches of precipitation at an elevation of 3,922 feet msl (at Anza), resulting in an estimated 10.43 inches of precipitation over the Hellhole Canyon sub-basin. The estimated monthly precipitation in each sub-basin has been tabulated (Appendix C).

Precipitation summary. Estimated average annual precipitation throughout the Borrego watershed ranges from approximately 5.8 inches in Borrego Valley to approximately 17.4 inches in Borrego Palm Canyon (Table 3). During the period of record, the estimated maximum annual precipitation throughout the Borrego watershed ranges from approximately 17.5 inches in Borrego Valley to approximately 40.9 inches in Borrego Palm Canyon. The estimated maximum annual precipitation throughout the watershed occurred at 8 of the 16 sub-basins, including Borrego Valley, during 1983. The maximum precipitation occurred in the other 8 sub-basins in 1941, prior to significant groundwater development from the valley (Table 3).

Stream Recharge

Runoff from the surrounding watershed is the source of surface water that infiltrates into the ground in Borrego Valley as stream recharge. The watershed is divided into 15 sub-basins that drain discrete portions of the watershed towards Borrego Valley (Figure 3.) Of these fifteen sources of stream recharge, surface-water gauging records exist for three. These records, together with the estimates of sub-basin areas and precipitation, provide the basis for empirically derived estimates of stream recharge at the twelve ungauged sources of stream recharge. Evaporative losses from streamflow into Borrego Valley were not considered and were assumed to be minimal. The majority of runoff from the watershed occurs during winter months when evaporation is relatively low. In addition, the alluvium around the perimeter of the valley is generally coarse grained and infiltration of runoff along the stream channels entering Borrego Valley is expected to occur rapidly. According to interviews with several long-term residents of Borrego Valley, surface water has reached the

Table 3. Estimated Annual Precipitation in Sub-Basins

DATE	DRAINAGE BASIN															
	Borrego Valley	East San Felipe Creek	Coyote Mountain	Indian Head Mountain	North-west Slopes	South Coyote Canyon	Dry Canyon	Lower San Felipe Creek	Pinyon Ridge	Henderson Canyon	South Borrego Palm Canyon	Upper San Felipe Creek	Culp-Tubb Canons	Hellhole Canyon	Coyote Creek	Borrego Palm Canyon
1945	13.29	12.00	12.00	11.09	11.00	10.18	10.17	11.35	11.64	12.29	12.35	14.65	15.40	15.82	17.16	24.91
1946	2.90	4.01	4.01	4.37	4.40	4.72	4.73	6.47	6.84	7.67	7.75	10.69	11.66	12.20	13.91	16.44
1947	4.18	4.01	4.01	3.86	3.84	3.70	3.69	4.34	4.48	4.80	4.84	5.99	6.37	6.59	7.26	11.99
1948	4.58	6.07	6.07	6.63	6.69	7.20	7.20	7.37	7.39	7.44	7.44	7.60	7.65	7.68	7.77	12.48
1949	3.58	3.99	3.99	4.07	4.08	4.16	4.16	5.53	5.83	6.49	6.57	8.93	9.72	10.15	11.53	13.48
1950	1.87	2.74	2.74	3.02	3.05	3.31	3.31	4.05	4.19	4.54	4.57	5.78	6.18	6.40	7.10	6.41
1951	6.33	7.56	7.56	7.98	8.02	8.40	8.40	9.77	10.06	10.70	10.77	13.06	13.82	14.23	15.57	17.48
1952	7.61	9.46	9.46	10.19	10.27	10.94	10.94	12.62	12.96	13.73	13.81	16.55	17.45	17.95	19.54	15.37
1953	1.29	1.62	1.62	1.76	1.77	1.89	1.89	2.31	2.40	2.60	2.62	3.32	3.55	3.68	4.09	4.36
1954	4.89	6.46	6.46	7.07	7.13	7.68	7.68	8.56	8.73	9.12	9.17	10.54	11.00	11.25	12.06	14.24
1955	4.89	4.49	4.49	4.09	4.05	3.69	3.69	5.00	5.30	5.98	6.05	8.44	9.23	9.67	11.06	13.74
1956	0.55	0.65	0.65	0.66	0.66	0.66	0.66	1.46	1.64	2.03	2.07	3.47	3.93	4.19	5.00	4.52
1957	3.50	4.83	4.83	5.41	5.47	5.99	6.00	7.47	7.76	8.45	8.52	10.93	11.72	12.16	13.57	18.89
1958	6.63	8.08	8.08	8.46	8.50	8.83	8.84	10.29	10.59	11.27	11.35	13.77	14.58	15.02	16.44	20.68
1959	5.86	5.65	5.65	5.33	5.30	5.01	5.01	5.76	5.93	6.33	6.37	7.76	8.22	8.48	9.29	16.04
1960	3.97	4.36	4.36	4.37	4.37	4.38	4.38	5.61	5.88	6.48	6.54	8.68	9.39	9.78	11.03	12.25
1961	2.11	1.90	1.90	1.71	1.69	1.52	1.51	2.20	2.36	2.71	2.74	3.98	4.39	4.62	5.34	8.49
1962	3.26	3.90	3.90	4.03	4.05	4.17	4.17	5.23	5.45	5.97	6.02	7.83	8.43	8.76	9.82	12.95
1963	6.66	7.26	7.26	7.46	7.48	7.65	7.66	8.96	9.23	9.86	9.93	12.15	12.88	13.28	14.58	17.35
1964	4.03	4.54	4.54	4.60	4.60	4.66	4.66	5.77	6.01	6.55	6.60	8.52	9.15	9.50	10.61	13.60
1965	7.39	8.94	8.94	9.38	9.42	9.82	9.82	11.62	11.99	12.85	12.94	15.96	16.96	17.51	19.27	23.97
1966	4.62	5.24	5.24	5.31	5.32	5.39	5.39	6.81	7.11	7.81	7.88	10.33	11.14	11.59	13.01	15.07
1967	5.37	6.40	6.40	6.64	6.66	6.88	6.88	8.88	9.30	10.27	10.37	13.78	14.91	15.53	17.52	15.91
1968	3.01	3.47	3.47	3.60	3.62	3.74	3.74	4.23	4.34	4.57	4.59	5.42	5.69	5.84	6.32	7.87
1969	5.40	6.71	6.71	7.14	7.18	7.57	7.57	9.36	9.74	10.59	10.68	13.68	14.67	15.22	16.97	22.02
1970	5.25	6.10	6.10	6.27	6.29	6.45	6.45	7.79	8.07	8.71	8.78	11.06	11.81	12.23	13.56	12.24
1971	2.28	3.08	3.08	3.41	3.44	3.74	3.74	4.63	4.81	5.22	5.26	6.72	7.20	7.46	8.31	13.87
1972	3.19	3.58	3.58	3.64	3.65	3.71	3.71	4.71	4.92	5.41	5.46	7.19	7.76	8.07	9.08	9.87
1973	3.02	3.79	3.79	4.04	4.07	4.30	4.31	5.48	5.72	6.28	6.34	8.31	8.96	9.32	10.47	12.83
1974	7.12	8.27	8.27	8.53	8.56	8.79	8.79	10.23	10.53	11.22	11.29	13.72	14.53	14.97	16.39	17.44
1975	4.60	4.86	4.86	4.78	4.78	4.71	4.71	5.78	6.01	6.54	6.60	8.48	9.10	9.44	10.54	14.94

Table 3 (continued). Estimated Annual Precipitation in Sub-Basins

DATE	DRAINAGE BASIN Borrego Valley	East San Felipe Creek	Coyote Mountain	Indian Head Mountain	North-west Slopes	South Coyote Canyon	Dry Canyon	Lower San Felipe Creek	Pinyon Ridge	Henderson Canyon	South Borrego Palm Canyon	Upper San Felipe Creek	Culp-Tubb Canons	Hellhole Canyon	Coyote Creek	Borrego Palm Canyon
1976	9.23	11.39	11.39	12.21	12.29	13.02	13.03	13.74	13.86	14.15	14.18	15.20	15.54	15.72	16.32	20.13
1977	7.21	8.21	8.21	8.40	8.42	8.60	8.60	9.52	9.72	10.16	10.20	11.76	12.27	12.55	13.46	17.71
1978	13.02	14.81	14.82	15.22	15.27	15.63	15.64	18.01	18.51	19.65	19.77	23.79	25.12	25.86	28.21	37.82
1979	7.77	9.53	9.53	10.12	10.19	10.72	10.73	11.58	11.74	12.11	12.15	13.48	13.91	14.15	14.93	19.99
1980	13.25	14.46	14.46	14.55	14.56	14.64	14.64	17.29	17.85	19.15	19.28	23.86	25.37	26.20	28.87	36.57
1981	5.31	6.11	6.11	6.29	6.31	6.47	6.47	7.18	7.32	7.66	7.69	8.87	9.26	9.47	10.16	14.93
1982	10.53	10.66	10.66	10.30	10.26	9.93	9.93	11.59	11.96	12.80	12.89	15.87	16.86	17.40	19.14	31.63
1983	17.49	18.27	18.26	18.04	18.02	17.81	17.81	19.08	19.36	19.99	20.06	22.32	23.06	23.48	24.79	40.93
1984	6.25	7.05	7.05	7.22	7.24	7.40	7.40	8.74	9.03	9.67	9.74	12.03	12.79	13.21	14.55	15.71
1985	4.81	5.28	5.28	5.36	5.37	5.43	5.43	6.12	6.27	6.60	6.64	7.82	8.21	8.42	9.11	15.40
1986	5.94	6.90	6.90	7.15	7.18	7.40	7.41	9.01	9.35	10.12	10.21	12.94	13.84	14.34	15.93	16.84
1987	5.68	6.72	6.72	7.04	7.08	7.37	7.38	8.16	8.32	8.69	8.73	10.01	10.44	10.68	11.43	16.98
1988	3.51	4.51	4.51	4.87	4.90	5.23	5.23	5.86	5.98	6.26	6.29	7.29	7.62	7.80	8.38	11.42
1989	1.94	2.50	2.50	2.70	2.72	2.90	2.91	3.63	3.77	4.11	4.15	5.35	5.75	5.97	6.67	7.88
1990	2.66	2.65	2.65	2.53	2.52	2.42	2.42	3.43	3.66	4.17	4.22	6.02	6.62	6.94	7.99	10.01
1991	8.74	9.58	9.58	9.67	9.68	9.76	9.76	10.62	10.81	11.22	11.27	12.74	13.23	13.50	14.36	25.47
1992	9.58	11.40	11.40	12.02	12.08	12.64	12.65	13.56	13.73	14.13	14.18	15.60	16.07	16.33	17.16	25.90
1993	10.78	12.58	12.58	13.08	13.14	13.59	13.60	14.80	15.04	15.60	15.66	17.63	18.28	18.63	19.78	34.18
1994	4.11	4.87	4.87	5.11	5.13	5.35	5.35	6.26	6.45	6.88	6.93	8.45	8.96	9.24	10.12	13.12
1995	5.85	7.24	7.24	7.72	7.77	8.20	8.21	8.80	8.91	9.17	9.20	10.11	10.41	10.58	11.11	21.87
1996	1.88	3.08	3.08	3.58	3.63	4.08	4.08	5.36	5.63	6.22	6.28	8.38	9.08	9.46	10.68	15.72
1997	5.17	6.24	6.24	6.62	6.66	7.00	7.00	7.26	7.30	7.40	7.41	7.76	7.88	7.94	8.15	17.51
1998	5.03	8.23	8.24	9.71	9.87	11.20	11.21	12.62	12.88	13.46	13.52	15.60	16.28	16.66	17.87	20.64
1999	4.00	4.85	4.86	5.25	5.29	5.65	5.65	6.03	6.10	6.25	6.27	6.82	7.01	7.11	7.43	8.17
2000	1.71	2.70	2.70	3.16	3.21	3.62	3.62	4.06	4.14	4.32	4.34	4.98	5.19	5.30	5.68	6.54
Low	0.55	0.65	0.65	0.66	0.66	0.66	0.66	1.46	1.64	2.03	2.07	3.32	3.55	3.68	4.09	4.36
Average	5.74	6.75	6.75	7.05	7.08	7.34	7.35	8.58	8.84	9.42	9.49	11.56	12.25	12.62	13.83	17.13
High	17.49	18.27	18.26	18.04	18.02	17.81	17.81	20.08	20.62	21.84	21.97	26.30	27.73	28.52	31.04	40.93

Note: Precipitation is in units of inches.

Borrego Sink only after the most high intensity precipitation events such as during 1980 and 1993, and most runoff infiltrates along streambeds near the perimeter of the basin. Annual stream recharge for the fifteen sub-basins was estimated for the period 1945 through 2000, as discussed in the following sections.

Gauged streams. Three streams in the Borrego watershed have been historically gauged by the USGS: Borrego Palm Creek, Coyote Creek, and San Felipe Creek (specifically that portion of San Felipe Creek upstream from Sentenac Canyon, referred to in this document as Upper San Felipe Creek). Currently, only the gauging station on Borrego Palm Creek is maintained, and it is operated in cooperation between the USGS and the Borrego Water District (BWD). Reported daily values of average instantaneous discharge were reduced to annual volumes of streamflow measured at the three gauged streams (Table 4). Some of the previous water budgets for the basin have based estimates of recharge on averages of these reported gauging records with some nominal amount of recharge added for other ungauged streams (BWD, 2001; DWR 1984b; Durbin and Berenbrock, 1985; Moyle, 1982; Mitten et al., 1988). Some water budgets have used even shorter periods than the full record length of the stream gauging records, and as such have been biased high because the period used in the recharge estimates coincides with a much wetter period than the average of the full period of record (BWD, 2001).

The period of record for stream gauging on Borrego Palm Creek is 50 years from 1951 to the present, although the gauging station was washed out in 1993, resulting in only partial records for 1993 and 1994. The period of record for Coyote Creek is 32 years, from 1951 through 1982, and the period of record for Upper San Felipe Creek is 24 years, from 1959 through 1982. Estimates of annual streamflow were made to complete the “missing” records for each of the three gauged streams for the full period from 1945 through 2000 as described below.

For the period 1945 through 1950, no stream gauging records exist for the three streams that were later gauged. Annual streamflow during the 1945 through 1950 period was estimated based on rainfall-runoff relationships for each of the three sub-basins. Figures 38 through 40 are plots of annual gauged streamflow versus annual precipitation for each of the three sub-basins. Though good correlation is not observed between annual streamflow and annual precipitation (R^2 ranging from 0.28 to 0.46), least squares best-fit lines were fit to the data plots and the relationships were used with annual precipitation

Table 4. Annual Streamflow at Gauged Stations within the Borrego Watershed

REPORTED DATA (USGS, 2001):				ESTIMATED COMPLETE RECORD 1945-2000:			
YEAR	Borrego Palm Creek	Coyote Creek	San Felipe Creek	YEAR	Borrego Palm Creek	Coyote Creek	San Felipe Creek
1945				1945	1433	2386	802
1946				1946	597	1827	331
1947				1947	158	679	0
1948				1948	206	768	0
1949				1949	305	1415	122
1950				1950	0	652	0
1951	274	2410		1951	274	2410	461
1952	982	2330		1952	982	2330	687
1953	238	1650		1953	238	1650	278
1954	303	1820		1954	303	1820	338
1955	357	1730		1955	357	1730	337
1956	226	1520		1956	226	1520	244
1957	152	420		1957	152	420	48
1958	718	1860		1958	718	1860	490
1959	138	1500	241	1959	138	1500	241
1960	149	1490	217	1960	149	1490	217
1961	38	1440	164	1961	38	1440	164
1962	128	1020	165	1962	128	1020	165
1963	59	1320	138	1963	59	1320	138
1964	114	1100	128	1964	114	1100	128
1965	174	1580	123	1965	174	1580	123
1966	266	1190	291	1966	266	1190	291
1967	115	1140	406	1967	115	1140	406
1968	121	888	93	1968	121	888	93
1969	716	963	246	1969	716	963	246
1970	127	1110	184	1970	127	1110	184
1971	55	908	113	1971	55	908	113
1972	9	980	65	1972	9	980	65
1973	258	412	90	1973	258	412	90
1974	47	1110	102	1974	47	1110	102
1975	65	353	87	1975	65	353	87
1976	97	448	149	1976	97	448	149
1977	312	1450	108	1977	312	1450	108
1978	770	1810	763	1978	770	1810	763
1979	2458	2390	426	1979	2458	2390	426
1980	5697	11260	4820	1980	5697	11260	4820
1981	1124	3364	323	1981	1124	3364	323

Table 4 (continued). Annual Streamflow at Gauged Stations within the Borrego Watershed

REPORTED DATA (USGS, 2001):				ESTIMATED COMPLETE RECORD 1945-2000:			
YEAR	Borrego Palm Creek	Coyote Creek	San Felipe Creek	YEAR	Borrego Palm Creek	Coyote Creek	San Felipe Creek
1982	1561	2955	863	1982	1561	2955	863
1983	4994			1983	4994	8975	3590
1984	1406			1984	1406	3129	1004
1985	967			1985	967	2414	688
1986	790			1986	790	2126	560
1987	514			1987	514	1676	361
1988	400			1988	400	1491	279
1989	228			1989	228	1210	155
1990	171			1990	171	1117	114
1991	600			1991	600	1816	423
1992	475			1992	475	1613	333
1993[a]	3786			1993	3786	7007	2719
1994				1994	269	1174	65
1995	1479			1995	1479	3248	1057
1996	293			1996	293	1316	202
1997	297			1997	297	1323	205
1998	1543			1998	1543	3353	1103
1999	285			1999	285	1303	196
2000	218			2000	218	1194	148
Total	36294	55921	10305	Total	39261	109134	27647
Number of Years of Record	48	32	24	Number of Years of Record	56	56	56
Average	756	1,748	429	Average	701	1,949	494

Notes:
Values of streamflow are in units of acre-feet.
a) Measured January through September 1993.

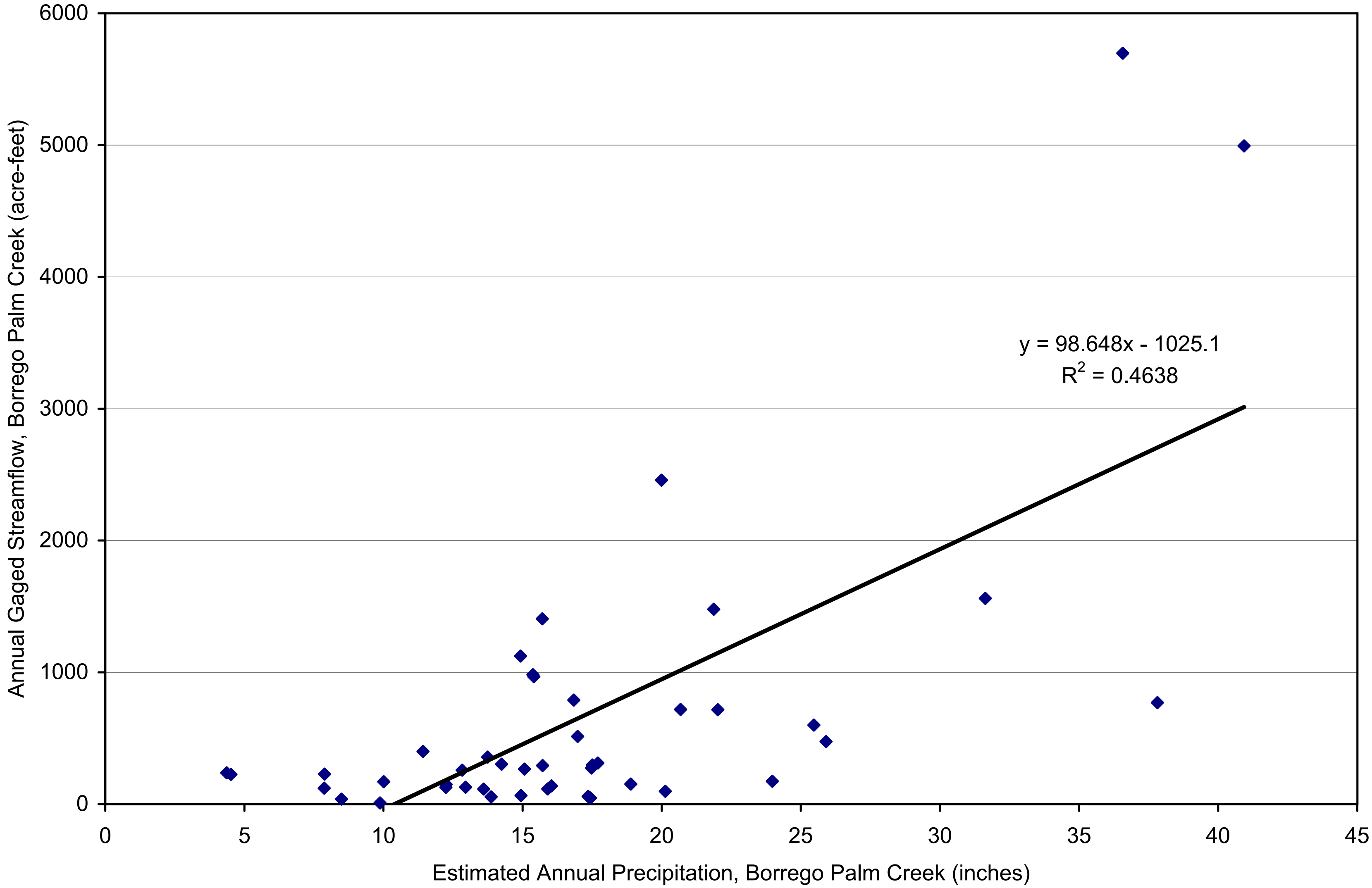


Figure 38. Runoff versus Rainfall, Borrego Palm Creek.

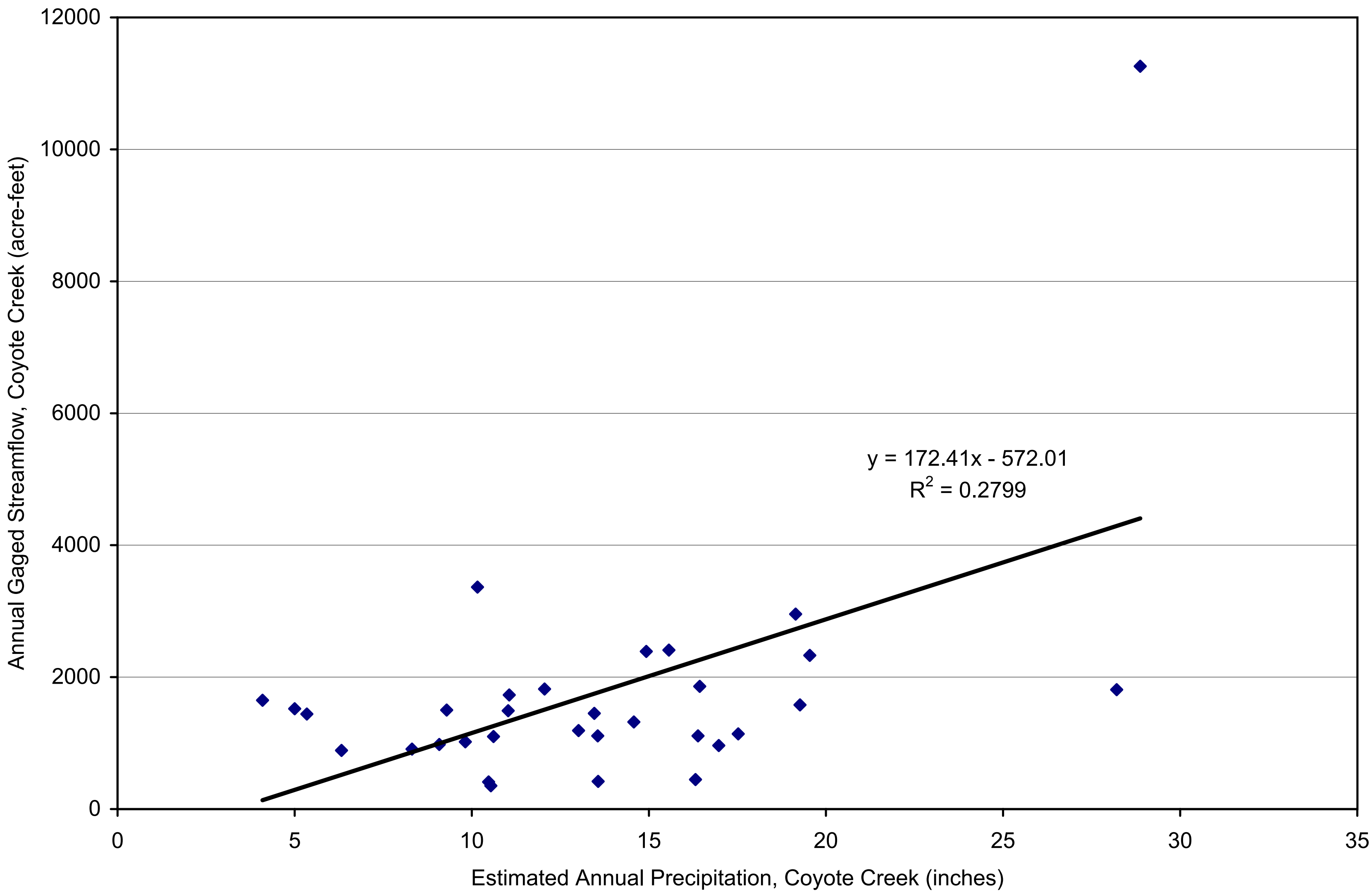


Figure 39. Runoff versus Rainfall, Coyote Creek.

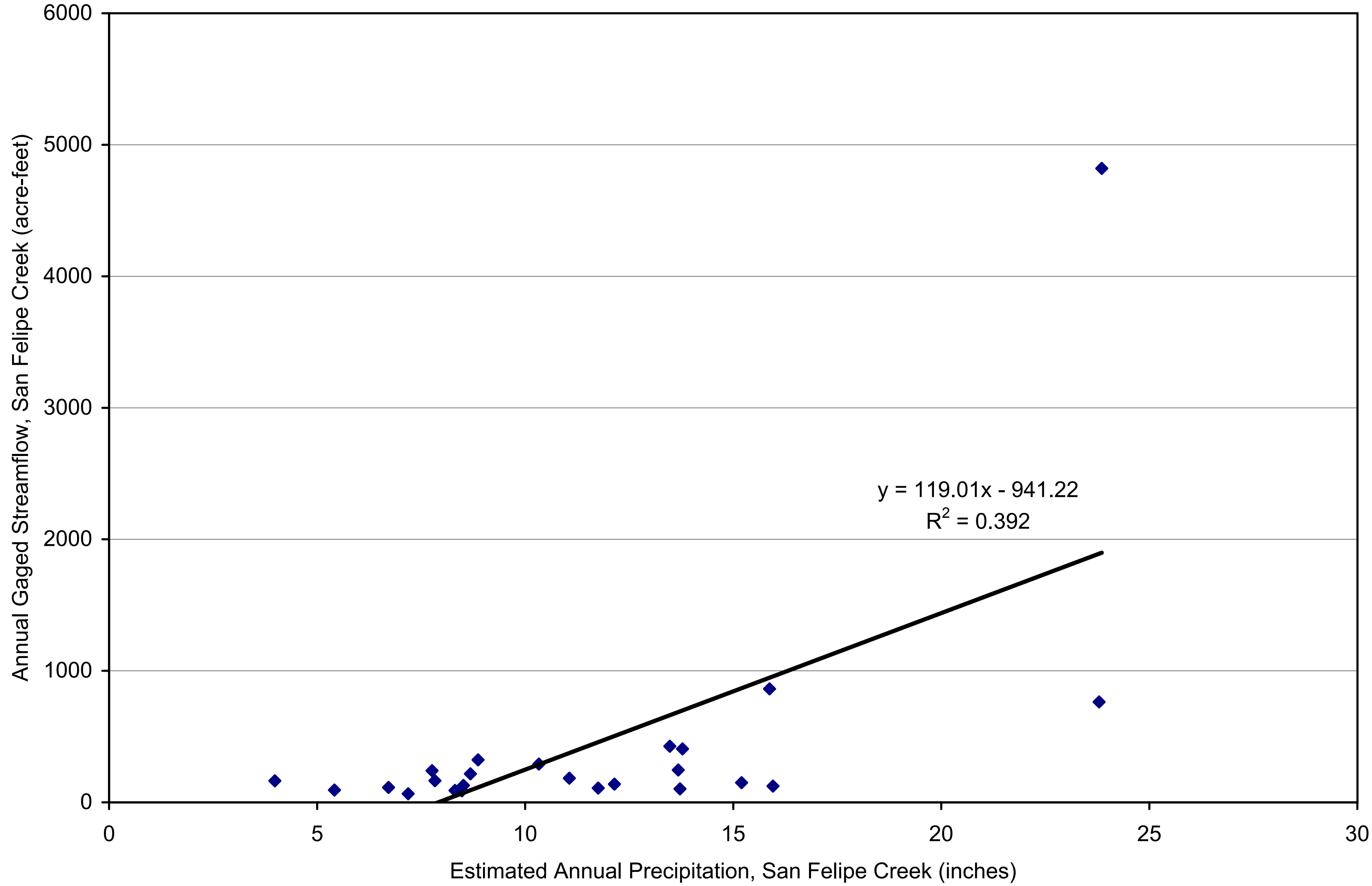


Figure 40. Runoff versus Rainfall, San Felipe Creek.

estimates for the three sub-basins to estimate annual streamflow on the three creeks during this early six-year period (Table 4).

For the period 1951 through 1958, stream gauging records exist for Borrego Palm Creek and Coyote Creek, but not for Upper San Felipe Creek. Estimates of annual streamflow for Upper San Felipe Creek during this period were made based on discharge relationships between annual gauged streamflow data for this creek and for Borrego Palm Creek and Coyote Canyon (Figures 41 to 43). Moderate to good correlation is observed for annual streamflow between the San Felipe Creek and the other two creeks (R^2 ranging from 0.86 to 0.94). Least squares best-fit lines were fit to the plots and the relationships were used to estimate annual streamflow for Upper San Felipe Creek during the eight-year period. Two estimates were obtained for streamflow on Upper San Felipe during this period, one from the streamflow relationship with Borrego Palm Creek and one from the streamflow relationship with Coyote Creek. These two estimates were weighted based on the correlation coefficients of the best-fit lines to provide a single estimate of annual streamflow for Upper San Felipe Creek during each of eight years during this period (Table 4).

During the 24-year period from 1959 through 1982 stream gauging occurred on all three streams. However, during the next 18-year period, from 1982 through 2000, only Borrego Palm Creek was gauged. Only partial records exist for Borrego Palm Creek during 1993 and 1994. Streamflow was calculated for these two years based on the rainfall-runoff relationship used to estimate the annual record for Borrego Palm Creek during the period 1945 through 1950 (Figure 38). However, because the streamflow calculated for Borrego Palm Creek in 1993 based on the rainfall-runoff relationship was 2,346 acre-feet while the measured streamflow through September 1993 was 3,786 acre-feet, the streamflow on Borrego Palm Creek in 1993 was assumed equal to the measured streamflow through September that year. For 1994, streamflow on Borrego Palm Creek was estimated based on the rainfall-runoff relationships described above. Estimates of annual streamflow on Coyote Creek and on Upper San Felipe Creek during this period are based on streamflow relationships between each of these creeks with Borrego Palm Creek (Figures 41 to 43).

Annual average streamflow, based on reported and estimated data over the 56 year period from 1945 through 2000, is approximately 700 af/yr on Borrego Palm Creek, approximately 1,950 af/yr on Coyote Creek, and approximately 500 af/yr on Upper San Felipe Creek (Table 4). These averages are very similar to those based only on observed data during the varying periods of records; approximately 750 af/yr on Borrego Palm Creek, approximately 1,750 af/yr on Coyote Creek, and approximately 430 af/yr on Upper San

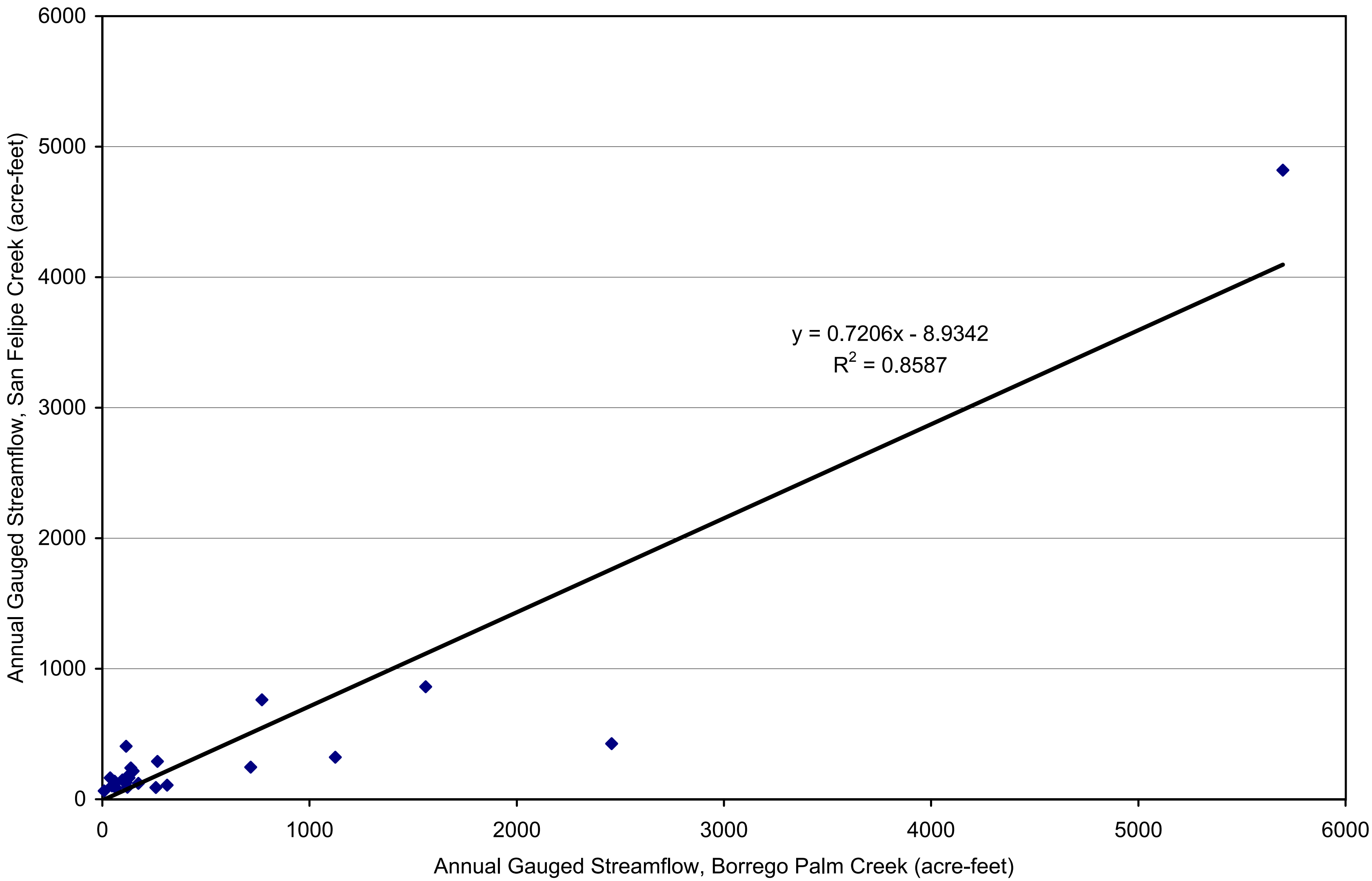


Figure 41. Gauged Streamflow, San Felipe Creek versus Borrego Palm Creek.

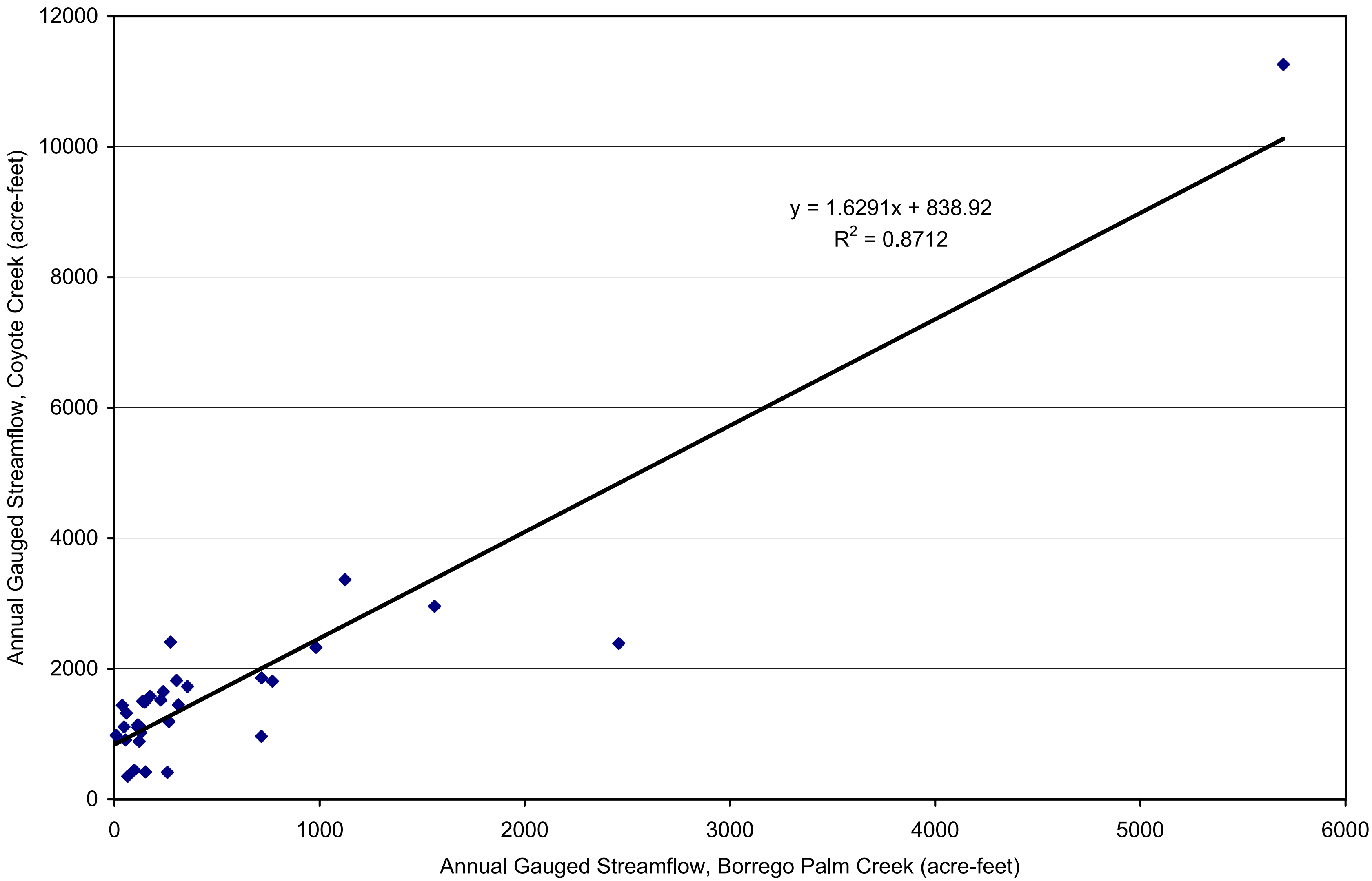


Figure 42. Gauged Streamflow, Coyote Creek versus Borrego Palm Creek.

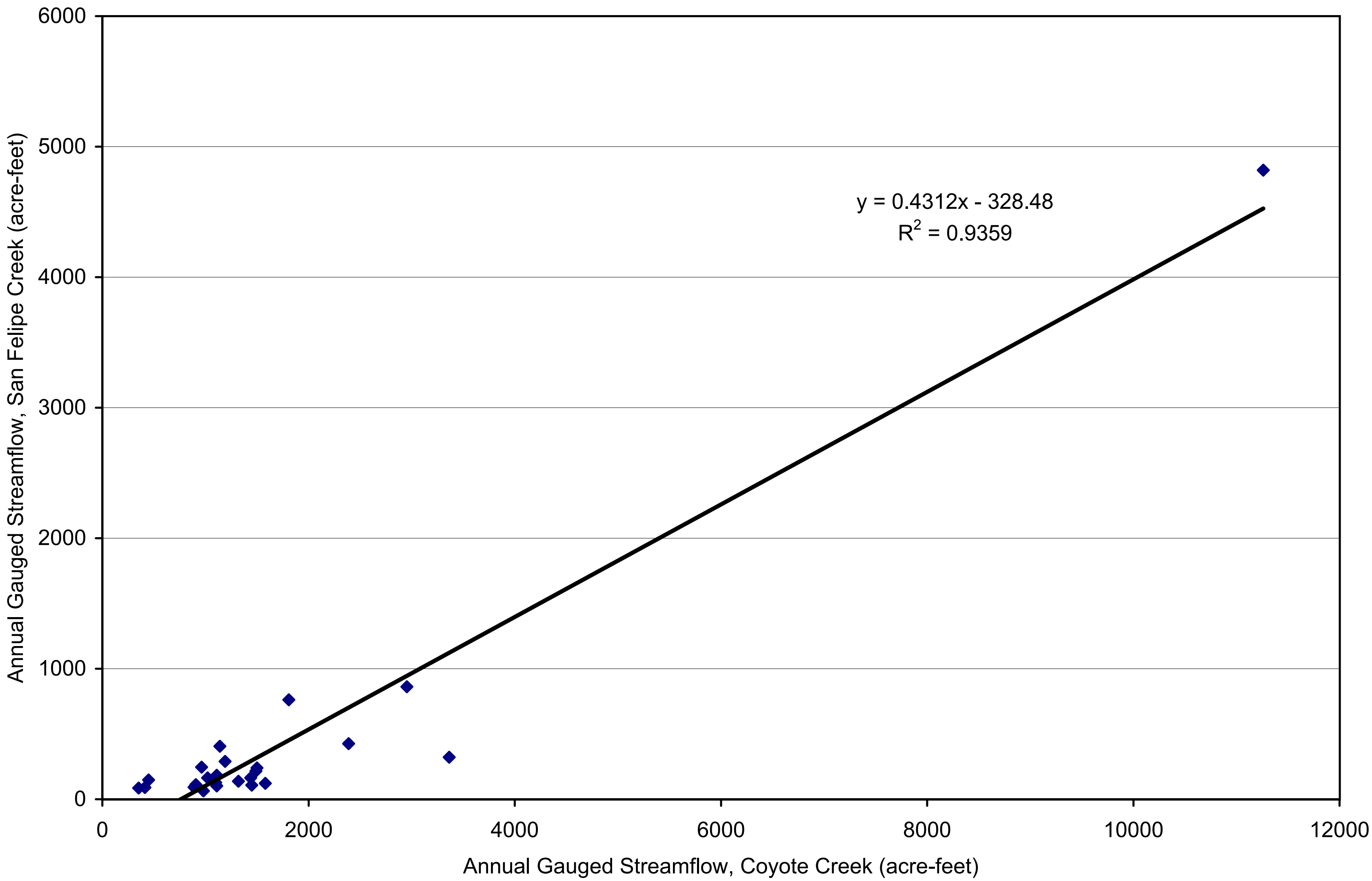


Figure 43. Gauged Streamflow, San Felipe Creek versus Coyote Creek.

Felipe Creek (Table 4). The total average annual streamflow for these three creeks, based on the 56-year period of observed and estimated data, is approximately 3,140 af/yr. Runoff from these three creeks provides the majority of recharge to Borrego Valley.

Ungauged streams. Annual runoff from the 12 ungauged sources of stream recharge to Borrego Valley was estimated for the period 1945 through 2000 using estimates for the 3 gauged sources of stream recharge described above. Runoff-runoff relationships between the 3 gauged creeks were evaluated in the section above and were found to have fair correlation. However, this type of relationship could not be used directly for the drainages that have never been gauged, because development of the runoff-runoff relationship requires some period of concurrent gauging of the streams. Therefore, some other relationship needed to be derived to relate streamflow from the gauged streams to the ungauged streams. Average annual stream discharge was compared to drainage area for the 3 gauged streams (Figure 44), and to average annual precipitation for the 3 gauged streams (Figure 45). Good correlation was not observed on either of these plots. The questionable correlation is probably due to different physiography, microclimates and local hydrologic cycles within each of the sub-basins that would make more precise predictions of runoff difficult to estimate. Because the majority of stream recharge occurs on the 3 streams that have been gauged, however, the simple relationships of area-runoff and rainfall-runoff were used to relate runoff on the gauged streams to runoff on the ungauged streams without introducing large errors in total recharge. Runoff-runoff relationships were derived between the gauged and ungauged streams that were based on the assumptions that (1) runoff from one drainage in the watershed can be related to runoff from another drainage in the watershed during the same time period, (2) runoff from a drainage can be related to the area of that drainage, and (3) runoff from a drainage can be related to the volume of precipitation that falls in that drainage area.

Independent estimates of annual stream runoff from each of the un-gauged sub-basins were made using runoff-runoff relationships with the gauged streams that were derived by both the area-runoff and precipitation-runoff methods. The area-runoff method assumes that the fraction of the area of the individual drainage to the area of the entire watershed is equal to the fraction of the runoff from that drainage to the total runoff from the entire watershed. For example, the sub-basins with the 3 gauged streams account for a total of approximately 66 percent of the total watershed area surrounding Borrego Valley. This method then assumes that approximately 66 percent of the total watershed runoff

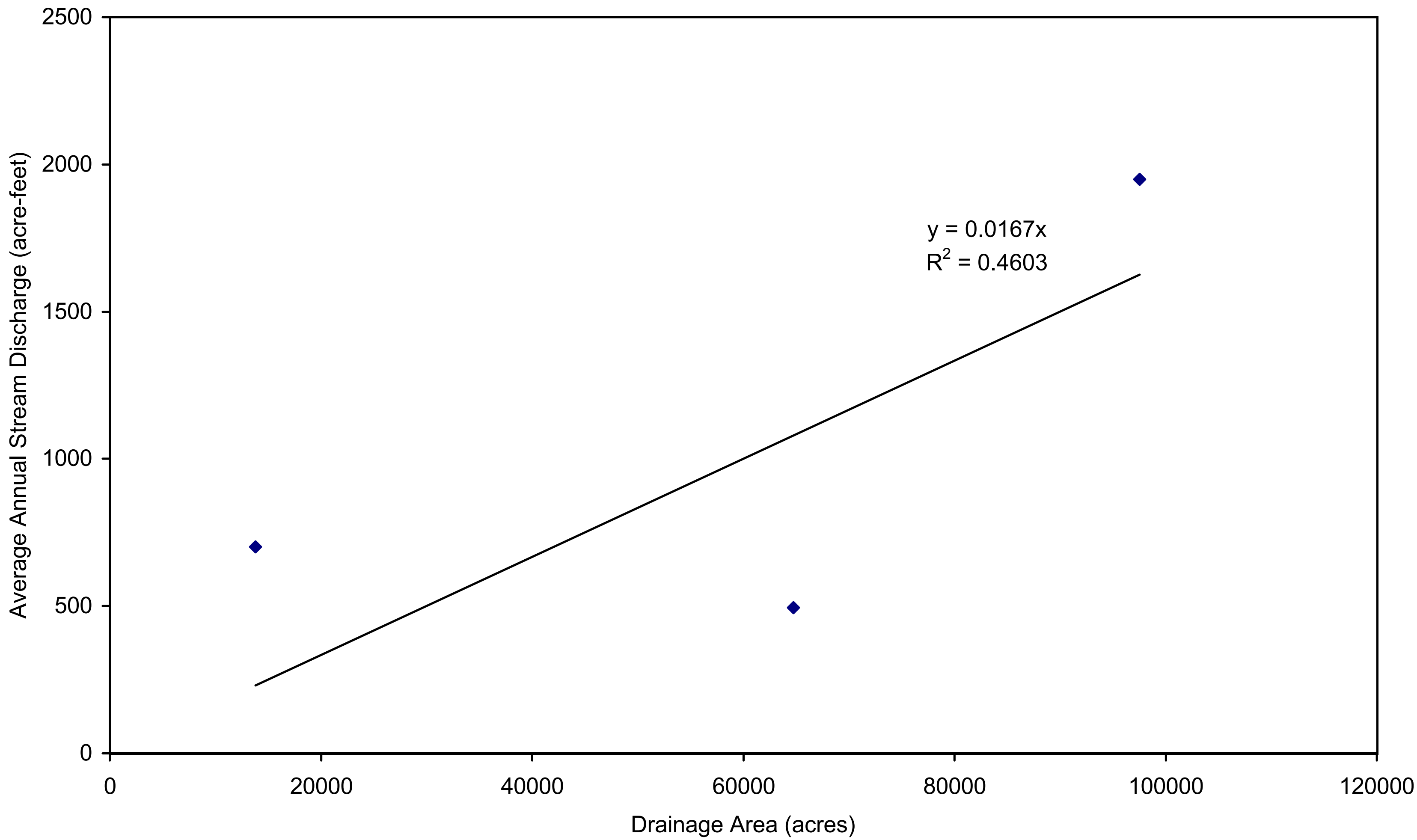


Figure 44. Average Annual Streamflow versus Drainage Area.

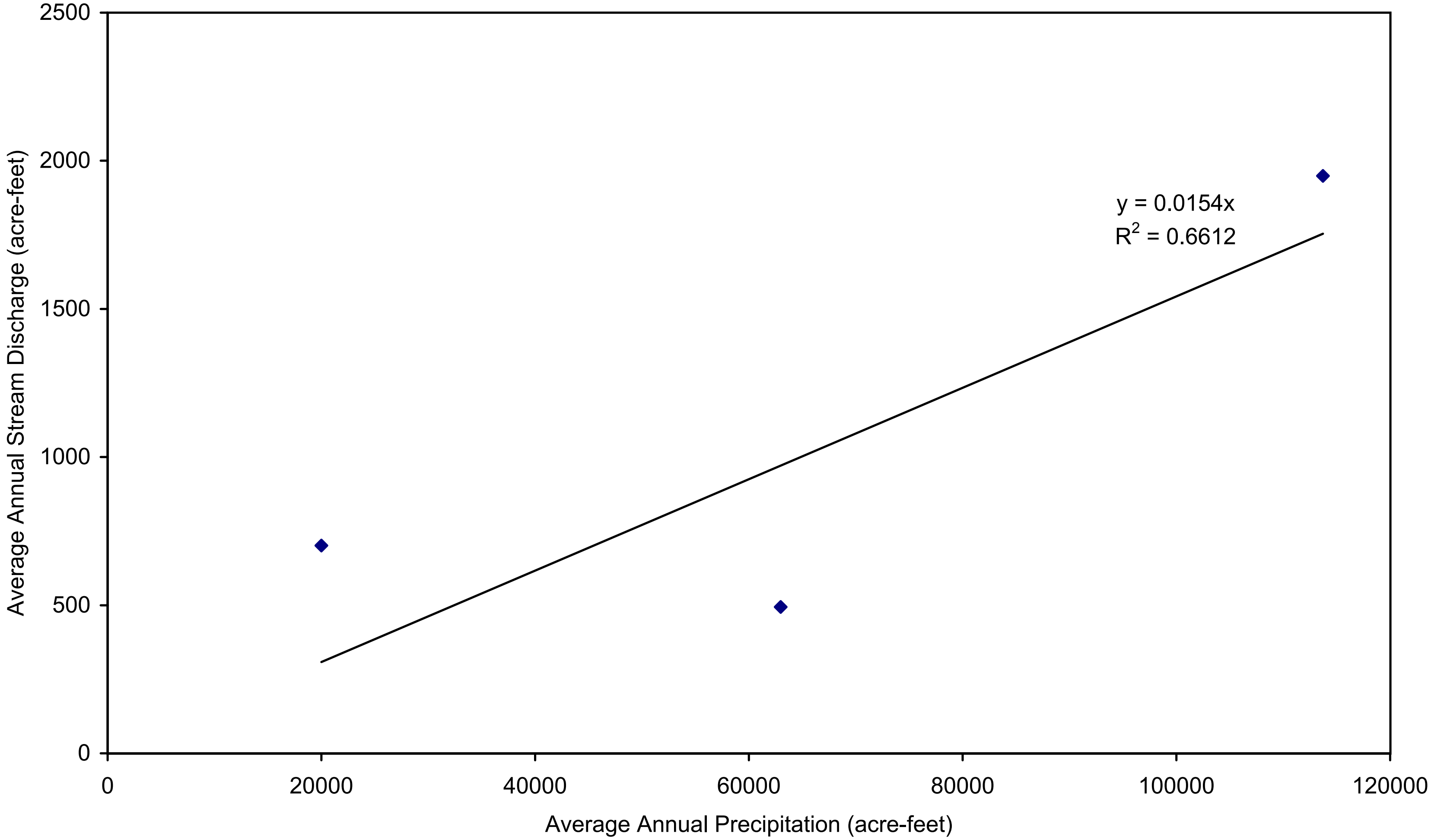


Figure 45. Average Annual Streamflow versus Average Annual Precipitation.

occurs from these 3 sub-basins. The total annual watershed runoff was estimated during the period 1945 to 2000 by taking the total runoff estimated for the 3 gauged streams each year and dividing that sum by approximately 66 percent, the fraction of the area of the three gauged sub-basin's to the total area of the watershed surrounding Borrego Valley. Or, $R = r_1+r_2+r_3 / ((a_1+a_2+a_3)/A)$, where R is the annual total watershed runoff, r_1, r_2, and r_3 are the annual values of runoff from the three gauged streams, a_1, a_2, and a_3 are the sub-basin areas of the 3 gauged streams, and A is the total watershed area surrounding Borrego Valley. Once the total runoff for the watershed was calculated for each year, the annual runoff from each of the ungauged sub-basins was then simply taken as that fraction of the total watershed runoff that is the fraction of that sub-basins area to the total watershed area. Or, $r_n = (a_n/A)*R$, where r_n is the estimated annual runoff for sub-basin n, and a_n is the area of sub-basin n. In this way, annual runoff from each of the 12 ungauged sub-basins was estimated for the period 1945 to 2000 (Appendix D).

The precipitation–runoff method is similar to the area runoff method, and assumes that the ratio of the volume of precipitation falling on the individual drainage to the total volume of precipitation falling on the entire watershed is equal to the ratio of the runoff from that drainage to the total runoff from the entire watershed. For example, the average volume of precipitation falling on the sub-basins with the 3 gauged streams account for a total of approximately 74 percent of the average total volume of precipitation falling on the entire watershed surrounding Borrego Valley. This method then assumes that approximately 74 percent of the total watershed runoff occurs from these 3 sub-basins. The total annual watershed runoff was estimated during the period 1945 to 2000 by taking the total runoff estimated for the 3 gauged streams each year and dividing that sum by approximately 74 percent, the fraction of the average volume of precipitation falling in the three gauged sub-basins to the average total volume of precipitation falling in the entire watershed surrounding Borrego Valley. Or, $R = r_1+r_2+r_3 / ((p_1+p_2+p_3)/P)$, where R is total annual watershed runoff, r_1, r_2, and r_3 are the annual values of runoff from the three gauged streams, p_1, p_2, and p_3 are the average annual volumes of precipitation falling in the sub-basins with the three gauged streams, and P is the average annual total volume of precipitation falling in the entire watershed surrounding Borrego Valley. Once the total runoff for the watershed was calculated for each year, the annual runoff from each of the ungauged sub-basins was then simply taken as that fraction of the total watershed runoff that is the fraction of that sub-basins average annual volume of precipitation to the total average annual volume of precipitation for the entire watershed. Or, $r_n = (p_n/P)*R$, where r_n

is the estimated annual runoff for sub-basin *n*, and p_n is the average annual volume of precipitation falling in sub-basin *n*. In this way, annual runoff from each of the 12 ungauged sub-basins was estimated for the period 1945 to 2000 (Appendix D.)

Average annual runoff based on the area-runoff method alone is approximately 4,740 af/yr, while average annual runoff based on the precipitation-runoff method is approximately 4,230 af/yr. Since neither of the two methods was significantly more accurate, the average of the two was assumed to represent annual runoff from the 12 ungauged sub-basins (Table 5; Appendix D). Average annual runoff from the entire watershed surrounding Borrego Valley, based on the average of the two methods, is estimated to be approximately 4,485 af/yr. Of this, 3,144 af/yr was contributed by the three gauged watersheds and the remaining 1,341 af/yr was estimated for the ungauged watersheds. Estimated average annual runoff for individual sub-basins ranges from 9 af/yr from South Borrego Palm Canyon to 1,950 af/yr from Coyote Creek. Estimated total annual runoff from the entire watershed during the period 1945 through 2000 ranges from 720 acre-feet in 1975 to over 31,000 acre-feet in 1980 (Table 5).

Table 5. Estimated Annual Runoff from Sub-Basins

Sub-Basin:	Borrego Palm Creek	Coyote Creek	Upper San Felipe Creek	Coyote Mountain	South Coyote Canyon	Northwest Slopes	Henderson Canyon	Indian Head Mountain	South Borrego Palm Canyon	Hellhole Canyon	Dry Canyon	Culp-Tubb Canyon	Pinyon Ridge	Lower San Felipe Creek	East San Felipe Creek	**Totals**
YEAR	Gage Records:			Ungaged Creeks (acre-feet):												
1945	1433	2386	802	89	51	49	84	19	13	204	31	200	129	1077	26	6591
1946	597	1827	331	53	31	29	50	12	8	121	18	119	77	642	15	3930
1947	158	679	0	16	9	9	15	4	2	37	6	36	23	195	5	1194
1948	206	768	0	19	11	10	18	4	3	43	7	42	27	227	5	1389
1949	305	1415	122	36	21	19	33	8	5	81	12	80	51	429	10	2628
1950	0	652	0	13	7	7	12	3	2	29	4	28	18	152	4	930
1951	274	2410	461	61	35	33	57	13	9	139	21	136	88	733	17	4487
1952	982	2330	687	77	45	42	73	17	11	176	27	173	111	932	22	5705
1953	238	1650	278	42	24	23	39	9	6	95	15	94	60	505	12	3089
1954	303	1820	338	47	27	26	45	10	7	108	17	107	69	573	14	3511
1955	357	1730	337	47	27	26	44	10	7	107	16	105	68	565	13	3458
1956	226	1520	244	38	22	21	36	8	6	88	13	86	55	464	11	2839
1957	152	420	48	12	7	7	11	3	2	27	4	27	17	145	3	885
1958	718	1860	490	59	34	32	56	13	9	135	21	133	86	715	17	4377
1959	138	1500	241	36	21	20	34	8	5	83	13	81	52	438	10	2681
1960	149	1490	217	36	21	20	34	8	5	82	12	80	52	432	10	2648
1961	38	1440	164	32	18	17	30	7	5	72	11	71	46	383	9	2343
1962	128	1020	165	25	15	14	24	5	4	58	9	57	37	306	7	1873
1963	59	1320	138	29	17	16	28	6	4	67	10	66	42	353	8	2164
1964	114	1100	128	26	15	14	24	6	4	59	9	58	37	313	7	1915
1965	174	1580	123	36	21	20	34	8	5	83	13	81	52	437	10	2678
1966	266	1190	291	34	19	18	32	7	5	77	12	76	49	407	10	2492
1967	115	1140	406	32	19	18	30	7	5	73	11	72	46	387	9	2370
1968	121	888	93	21	12	12	20	5	3	49	7	48	31	257	6	1572
1969	716	963	246	37	21	20	35	8	5	85	13	83	54	449	11	2746
1970	127	1110	184	27	16	15	26	6	4	63	10	62	40	331	8	2027
1971	55	908	113	21	12	11	20	5	3	47	7	47	30	251	6	1535
1972	9	980	65	20	12	11	19	4	3	46	7	46	29	246	6	1504
1973	258	412	90	15	8	8	14	3	2	33	5	33	21	177	4	1084
1974	47	1110	102	24	14	13	23	5	4	55	8	55	35	293	7	1796
1975	65	353	87	10	6	5	9	2	1	22	3	22	14	118	3	720
1976	97	448	149	13	8	7	13	3	2	31	5	30	19	162	4	990
1977	312	1450	108	36	21	20	34	8	5	82	13	81	52	436	10	2668

Table 5 (continued). Estimated Annual Runoff from Sub-Basins

Sub-Basin:	Borrego Palm Creek	Coyote Creek	Upper San Felipe Creek	Coyote Mountain	South Coyote Canyon	Northwest Slopes	Henderson Canyon	Indian Head Mountain	South Borrego Palm Canyon	Hellhole Canyon	Dry Canyon	Culp-Tubb Canyon	Pinyon Ridge	Lower San Felipe Creek	East San Felipe Creek	**Totals**
YEAR	Gage Records:			Ungaged Creeks (acre-feet):												
1978	770	1810	763	64	37	35	61	14	9	147	22	145	93	779	18	4769
1979	2458	2390	426	102	59	56	96	22	15	232	35	228	147	1229	29	7524
1980	5697	11260	4820	420	243	231	395	91	61	959	146	943	607	5074	120	31068
1981	1124	3364	323	93	54	51	87	20	14	212	32	208	134	1121	27	6864
1982	1561	2955	863	104	60	57	98	23	15	237	36	233	150	1253	30	7674
1983	4994	8975	3590	339	196	186	319	74	49	773	118	760	490	4091	97	25049
1984	1406	3129	1004	107	62	59	101	23	16	244	37	240	154	1291	31	7903
1985	967	2414	688	79	45	43	74	17	11	179	27	176	113	948	22	5805
1986	790	2126	560	67	39	37	63	15	10	153	23	150	97	810	19	4959
1987	514	1676	361	49	28	27	46	11	7	112	17	110	71	595	14	3640
1988	400	1491	279	42	24	23	39	9	6	96	15	94	60	506	12	3096
1989	228	1210	155	31	18	17	29	7	4	70	11	69	44	371	9	2274
1990	171	1117	114	27	16	15	25	6	4	62	9	61	39	327	8	2001
1991	600	1816	423	55	32	30	52	12	8	125	19	123	79	662	16	4051
1992	475	1613	333	47	27	26	44	10	7	107	16	105	68	564	13	3454
1993	3786	7007	2719	261	151	143	245	57	38	595	91	585	377	3149	75	19277
1994	269	1174	65	29	17	16	27	6	4	66	10	65	42	351	8	2151
1995	1479	3248	1057	112	64	61	105	24	16	255	39	250	161	1348	32	8252
1996	293	1316	202	35	20	19	33	8	5	80	12	78	51	422	10	2584
1997	297	1323	205	35	20	19	33	8	5	80	12	79	51	425	10	2603
1998	1543	3353	1103	116	67	64	109	25	17	264	40	260	167	1398	33	8558
1999	285	1303	196	34	20	19	32	7	5	79	12	77	50	416	10	2546
2000	218	1194	148	30	17	17	28	7	4	69	10	68	43	364	9	2226
Low	0	353	0	10	6	5	9	2	1	22	3	22	14	118	3	720
Average	**701**	**1949**	**494**	**61**	**35**	**33**	**57**	**13**	**9**	**138**	**21**	**136**	**88**	**733**	**17**	**4485**
High	5697	11260	4820	420	243	231	395	91	61	959	146	943	607	5074	120	31068

Bedrock Recharge

Bedrock recharge occurs as groundwater flows from the bedrock underlying adjacent drainage areas through the bedrock-alluvial contact around the basin perimeter, such as the Northwest Slopes, Henderson Canyon and Pinyon Ridge (Figures 3 and 7). Flow through crystalline bedrock is typically several orders of magnitude less than flow through alluvial materials, however, the slow seepage from bedrock can be a significant source of recharge when large areas of the bedrock are in contact with the aquifer. Groundwater flow through the surrounding bedrock is expected to approximately mirror topography, discharging to the regional topographic low in Borrego Valley. Sources considered to provide significant bedrock recharge to Borrego Valley are those sub-basins in the surrounding watershed with bedrock topography that drains directly towards the groundwater basin and which have large areas of direct bedrock surface contact with the aquifer system. Of the 15 surface water drainage sub-basins, 9 were considered to provide bedrock recharge directly to the groundwater basin. Groundwater seepage through bedrock in the remaining six surface water drainage sub-basins is expected to either be forced to the surface and enter Borrego Valley as streamflow due to narrow channels and/or bedrock highs at the toe of the drainage areas, or to flow towards other local topographic lows within the regional watershed, such as San Felipe Valley or Collins Valley (Figures 3 and 7). The nine bedrock drainage areas considered to provide bedrock recharge to Borrego Valley are:

1. Coyote Mountain,
2. Dry Canyon,
3. Hellhole Canyon,
4. Henderson Canyon,
5. Indian Head Mountain,
6. Northwest Slopes,
7. Pinyon Ridge,
8. South Borrego Palm Canyon, and
9. South Coyote Canyon.

As noted above, previous water budgets have either not considered bedrock recharge or have overly simplified this source of recharge to the groundwater basin (BWD, 2001; DWR, 1984b; Durbin and Berenbrock, 1985; Moyle, 1982; Mitten et al., 1988). During this evaluation, bedrock recharge was estimated from the 9 bedrock drainage areas for the period 1945 through 2000 using a mass balance approach, as described below.

The mass balance approach used is an attempt to account for all water introduced as precipitation to the sub-basins contributing bedrock recharge to the Borrego Valley groundwater basin. Conceptually, once precipitation has reached a watershed, some fraction of it will run off as surface water flow, some is used by plant transpiration or lost to the atmosphere as evapotranspiration, some is retained in the soil column as soil moisture, and any remaining water has the potential to become recharge to the bedrock complex underlying the soil in that drainage area. In this study, bedrock recharge was calculated for the period 1945 through 2000 using the computer program *Recharg2* (Huntley, 1990). The program is based on the Thornthwaite Method, which utilizes a soil moisture budget approach and is one of the more traditional methods of estimating groundwater recharge (Huntley, 1990; Thornthwaite and Mather, 1955 and 1957). *Recharg2* solves the following equation to calculate groundwater recharge:

$$R_i = P_i - RO_i - PET_i - (SM_c - SM_i)$$

where:

R_i = Recharge during the ith month.
P_i = Precipitation during the ith month.
RO_i = Run-off during the ith month.
PET_i = Potential evapotranspiration during the ith month.
SM_c = Soil moisture capacity
SM_i = Soil moisture at beginning of ith month.

The program calculates runoff internally as $RO_i = RO_{max} * (SM_i/SM_c)$, where RO_{max} is the maximum percent runoff (max runoff). The program is typically run iteratively while varying the input max runoff value and soil moisture capacity to evaluate a range of results. Thus, input to the program *Recharg2* included monthly precipitation, PET, and a range of max runoff and soil moisture capacity for each of the sub-basins considered to provide bedrock recharge to Borrego Valley. Estimates of monthly precipitation for each sub-basin were made, as described above. Estimates of the other input variables are discussed below.

Average monthly PET for each sub-basin was estimated for the period 1945 through 2000. Estimates of average monthly PET were made rather than attempting to estimate actual monthly PET during this period because evaporation data are sparse, and because reported evaporation tends to vary little about the monthly means. Three evaporation stations were identified in the regional vicinity of the Borrego watershed that were considered representative of elevations and climatic zones throughout the watershed. Data were compiled from the three evaporation stations: U.S. Date Garden at Indio, Henshaw Reservoir, and Morena Reservoir (Table 6) (California Department of Public Works, 1948 and 1955). Reported average annual pan evaporation ranges from approximately 84 inches at the U.S. Date Garden in Indio to approximately 66 inches at both Henshaw and Morena

Table 6. Evaporation in the Vicinity of the Borrego Watershed

Reported Pan Evaporation (California Department of Public Works, 1948 and 1955):

LOCATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
US Date Garden, Indio	2.60	3.50	6.00	8.40	10.80	11.60	11.20	10.20	7.80	5.60	3.40	2.70	83.80
Henshaw Reservoir	2.00	2.13	3.32	4.58	7.11	8.68	10.33	9.88	7.54	5.29	3.26	2.06	66.18
Morena Reservoir	2.11	2.57	3.89	4.90	6.43	8.34	9.82	9.22	7.42	5.33	3.27	2.51	65.81

Reported Evaporation Station Information (California Department of Public Works, 1948 and 1955):

LOCATION	ELEVATION	YEARS OF RECORD	PAN TYPE	PAN COEEF
US Date Garden, Indio	20	8	Ground Pan	0.90
Henshaw Reservoir	2700	34	Ground Pan	0.90
Morena Reservoir	3045	20	Ground Pan	0.90

Calculated Potential Evapotranspiration:

LOCATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
US Date Garden, Indio	2.34	3.15	5.40	7.56	9.72	10.44	10.08	9.18	7.02	5.04	3.06	2.43	75.42
Henshaw Reservoir	1.80	1.92	2.99	4.12	6.40	7.81	9.30	8.89	6.79	4.76	2.93	1.85	59.56
Morena Reservoir	1.90	2.31	3.50	4.41	5.79	7.51	8.84	8.30	6.68	4.80	2.94	2.26	59.23

Note: Evaporation is reported in units of inches; elevation is in units of feet mean sea level.

Reservoirs. A ground pan type of evaporation pan was used to measure evaporation at all three stations, with reported pan coefficients for ground pans of 0.9. Reported monthly pan evaporation from each station was multiplied by the pan coefficient to obtain monthly PET. Average annual PET ranged from over 75 inches at the U.S. Date Garden in Indio to approximately 60 inches at both Henshaw and Morena Reservoirs.

Average monthly PET in each sub-basin of the Borrego watershed was estimated based on monthly PET-elevation relationships. Average monthly PET calculated at the three evaporation stations was plotted against elevation at the locations of the evaporation stations (Figures 46 through 48). Good correlation between average monthly PET and elevation was observed for all months with the exceptions of August and December, with moderate correlation for the month of February. A least squares best-fit line was fit to the plot for each month and the equations of the best-fit lines were used to calculate average monthly PET for each sub-basin using the area weighted average elevation for each basin. Estimated average annual evaporation for the sub-basins ranges from approximately 51 inches at Borrego palm Canyon to approximately 67 inches at East San Felipe Creek, with an average annual PET of over 71 inches in Borrego Valley (Table 7).

Estimates of the soil moisture capacity in the sub-basins considered to contribute bedrock recharge to Borrego Valley were based on reported soil properties for soil types that have been mapped in the vicinity and described by the U.S. Department of Agriculture (USDA, 1973). Much of the Borrego watershed, especially the mountainous areas of the surrounding watershed, lies within the Anza Borrego Desert State Park. The USDA did very little, if any, mapping of soil types within the State Park boundary and as a result, the soil map coverage is limited in those sub-basins considered to contribute bedrock recharge to Borrego Valley. Nevertheless, a review of the soil maps indicated that either portions of the sub-basins were mapped, or soil in the general vicinity was mapped. Generally two soil associations, predominantly the Tollhouse-La Posta-Rock and to a lesser extent the Sheephead, were found to occur throughout most of the area to the west of Borrego Valley. In addition, many of the steep rocky slopes in the surrounding watershed were mapped as Acid Igneous Rock with no real soil cover. In these areas, very little infiltration is expected and runoff would typically be very high. Reported properties for these soil associations have been summarized in Table 8 (USDA, 1973). Soil moisture capacity was calculated based on the reported available water capacity and the depths of soils. It should be noted here that the reported soil properties are for associations of soils and not the individual mapped soil. For example, the Sheephead soil association has two separately mapped soil units,

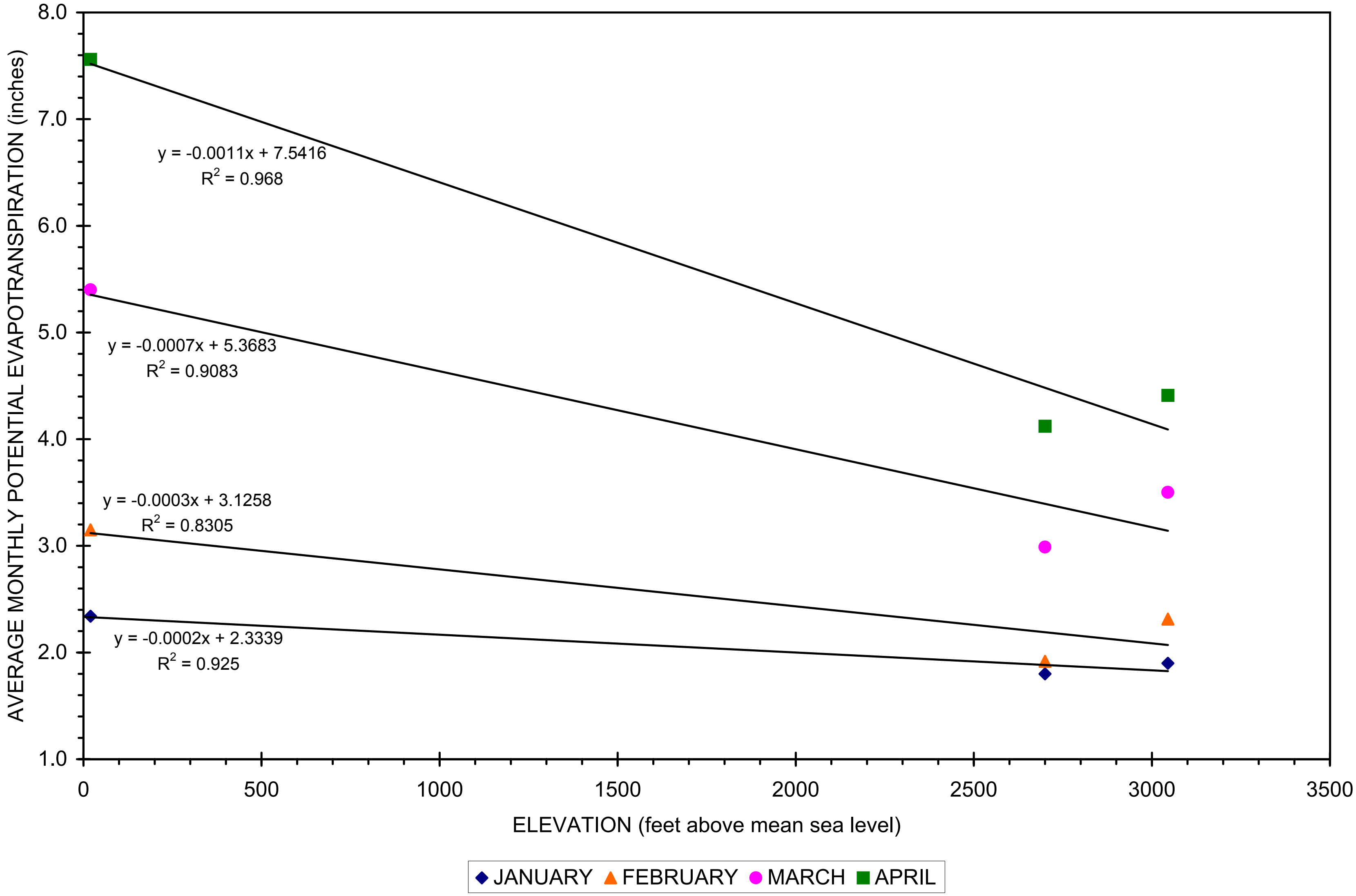


Figure 46. Average Monthly Evaporation versus Elevation in the Vicinity of the Borrego Watershed - January through April.

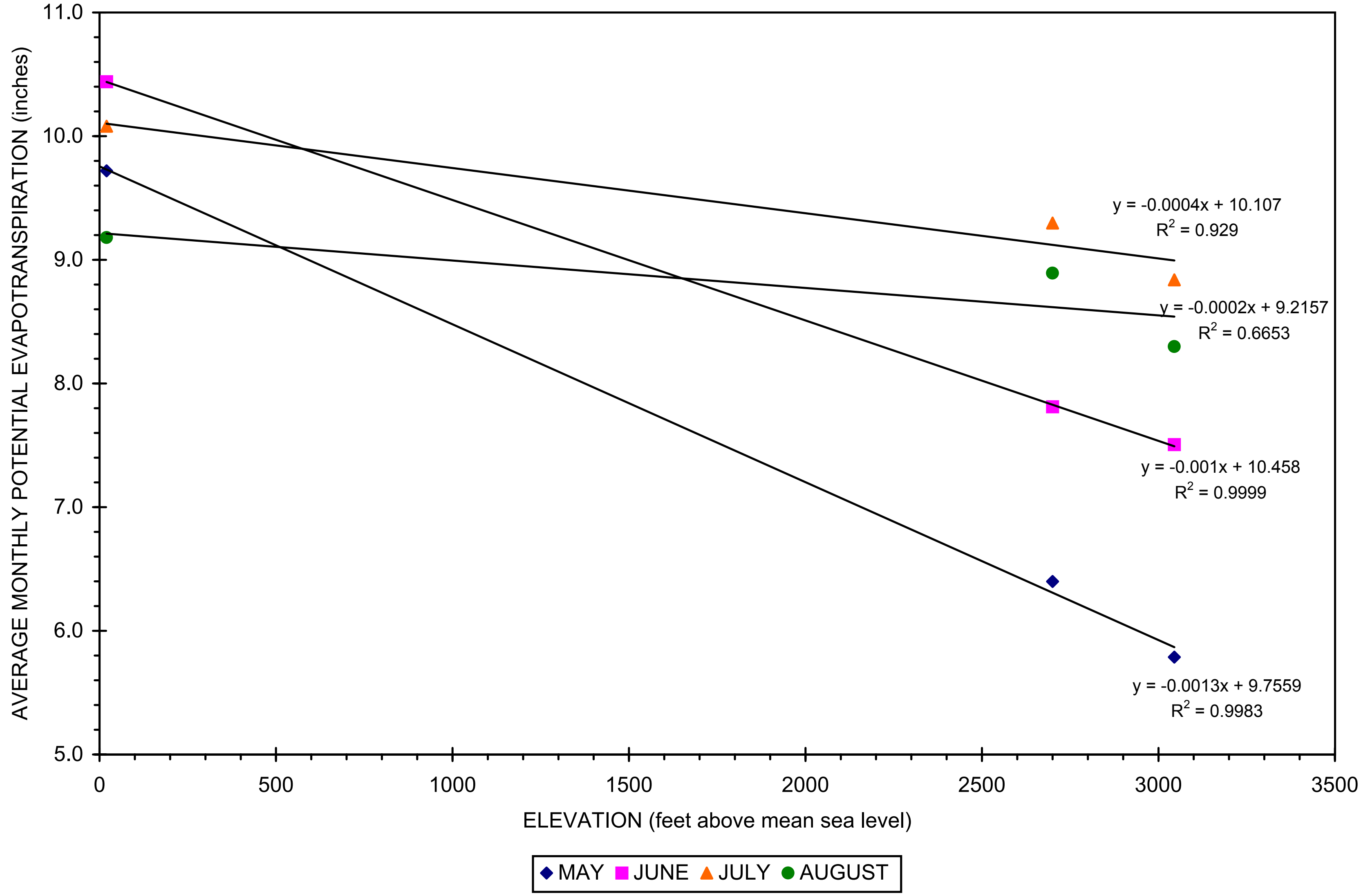


Figure 47. Average Monthly Evaporation versus Elevation in the Vicinity of the Borrego Watershed - May through August.

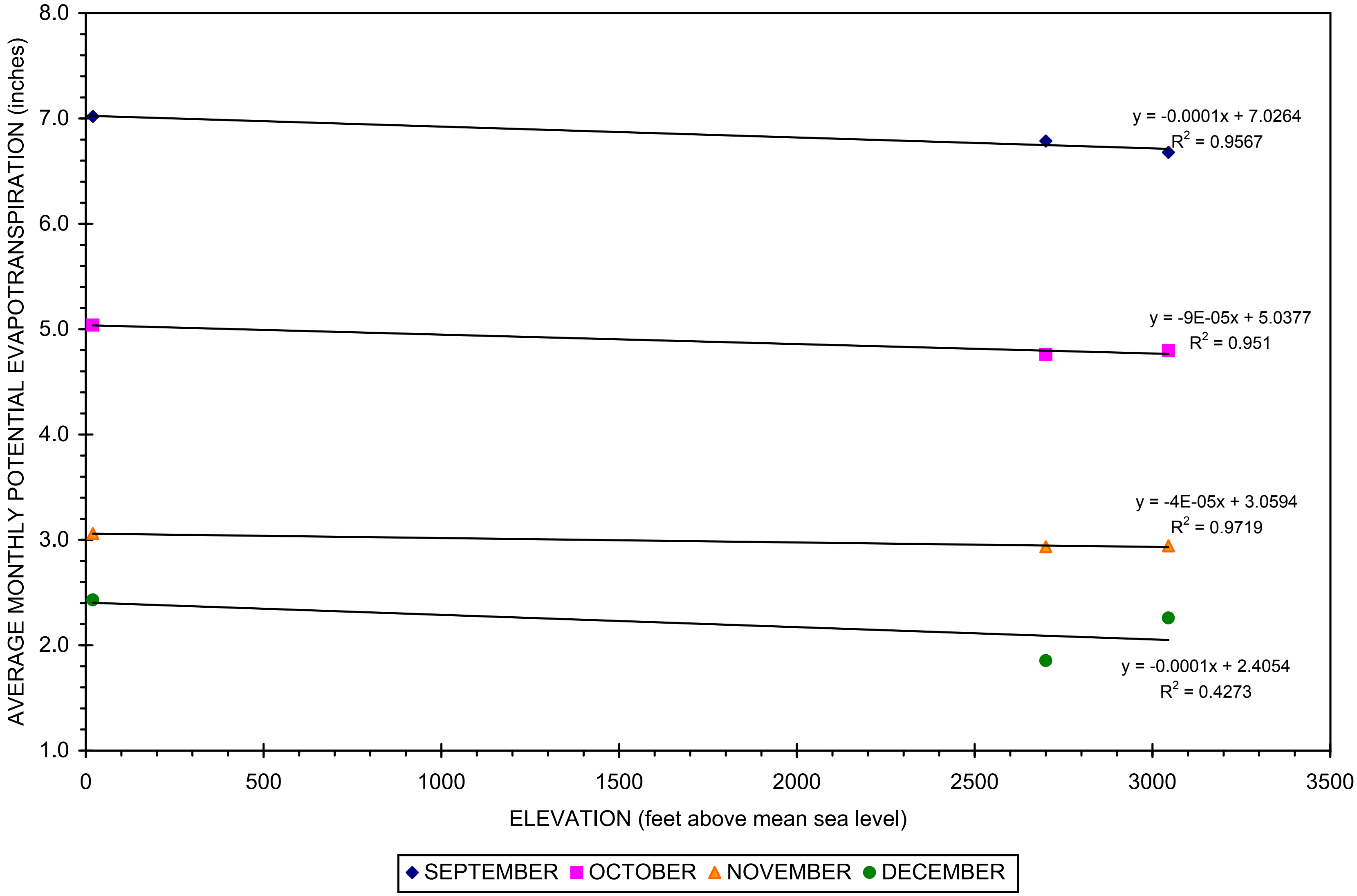


Figure 48. Average Monthly Evaporation versus Elevation in the Vicinity of the Borrego Watershed - September through December.

Table 7. Estimated Average Monthly Evaporation from the Sub-Basins

BASIN	AREA WEIGHTED AVERAGE ELEVATION (feet mean sea level)	ESTIMATED POTENTIAL EVAPOTRANSPIRATION (inches)												
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
BORREGO VALLEY	756	5.00	3.03	2.33	2.18	2.90	4.84	6.71	8.77	9.70	9.80	9.06	6.95	71.28
EAST SAN FELIPE CREEK	1528	4.96	3.00	2.25	2.03	2.67	4.30	5.86	7.77	8.93	9.50	8.91	6.87	67.05
COYOTE MOUNTAIN	1529	4.96	3.00	2.25	2.03	2.67	4.30	5.86	7.77	8.93	9.50	8.91	6.87	67.04
INDIAN HEAD MOUNTAIN	1884	4.94	2.98	2.22	1.96	2.56	4.05	5.47	7.31	8.57	9.35	8.84	6.84	65.09
NORTHWEST SLOPES	1921	4.94	2.98	2.21	1.95	2.55	4.02	5.43	7.26	8.54	9.34	8.83	6.83	64.89
SOUTH COYOTE CANYON	2241	4.93	2.97	2.18	1.89	2.45	3.80	5.08	6.84	8.22	9.21	8.77	6.80	63.13
DRY CANYON	2245	4.93	2.97	2.18	1.88	2.45	3.80	5.07	6.84	8.21	9.21	8.77	6.80	63.11
LOWER SAN FELIPE CREEK	2583	4.91	2.96	2.15	1.82	2.35	3.56	4.70	6.40	7.88	9.07	8.70	6.77	61.25
PINYON RIDGE	2645	4.91	2.95	2.14	1.80	2.33	3.52	4.63	6.32	7.81	9.05	8.69	6.76	60.91
HENDERSON CANYON	2786	4.90	2.95	2.13	1.78	2.29	3.42	4.48	6.13	7.67	8.99	8.66	6.75	60.14
SOUTH BORREGO PALM CANYON	2801	4.90	2.95	2.13	1.77	2.29	3.41	4.46	6.11	7.66	8.99	8.66	6.75	60.06
UPPER SAN FELIPE CREEK	3300	4.87	2.93	2.08	1.67	2.14	3.06	3.91	5.47	7.16	8.79	8.56	6.70	57.32
CULP-TUBB CANYONS	3465	4.86	2.92	2.06	1.64	2.09	2.94	3.73	5.25	6.99	8.72	8.52	6.68	56.41
HELLHOLE CANYON	3556	4.86	2.92	2.05	1.62	2.06	2.88	3.63	5.13	6.90	8.68	8.50	6.67	55.91
COYOTE CREEK	3847	4.85	2.91	2.02	1.56	1.97	2.68	3.31	4.75	6.61	8.57	8.45	6.64	54.31
BORREGO PALM CANYON	4514	4.81	2.88	1.95	1.43	1.77	2.21	2.58	3.89	5.94	8.30	8.31	6.58	50.65
LOW		4.81	2.88	1.95	1.43	1.77	2.21	2.58	3.89	5.94	8.30	8.31	6.58	50.65
AVERAGE		4.91	2.95	2.15	1.81	2.35	3.55	4.68	6.38	7.86	9.07	8.70	6.77	61.16
HIGH		5.00	3.03	2.33	2.18	2.90	4.84	6.71	8.77	9.70	9.80	9.06	6.95	71.28

SpE2 and SpG2, which vary in the range of slopes on which the soils are found. Therefore, although the individual soil units found in or near the watershed to the west of Borrego Valley are listed in Table 8, the soil properties listed are typical for the associations in which the individual soil types are members. In this case both soil units listed in Table 8 are the steeper end members of the range of slopes of their respective soil associations, and as such, soil might be expected to be thinner on the steeper slopes than for the more gentle slopes. The soil moisture capacities calculated for the soil associations in which these individual soils belong range from 0.6 to 2.16 inches for the Tollhouse soil and 1.38 to 4.26 inches for the Sheephead soil. Given that the Tollhouse soil, and to a lesser extent the Sheephead soil, was predominantly found to occur in or near the sub-basins of interest, and that some of the area has been mapped as Acid Igneous Rock with no real soil moisture capacity, the range of soil moisture capacities listed for the Tollhouse soil associated are considered intermediate values that are likely to represent the soil over much of the sub-basins. Therefore, the range of soil moisture capacity calculated for the Tollhouse soil, 0.6 to 2.16 inches, was used in the bedrock recharge analysis.

Table 8. Typical Soil Properties of the Borrego Watershed

Source: US Department of Agriculture (USDA), 1973:					CALCULATED SOIL MOISTURE CAPACITY (inches)
SOIL NAME	USDA MAP SYMBOL	SLOPE (%)	SOIL DEPTH (feet)	AVAILABLE WATER CAPACITY (inches/inch of soil)	
Acid igneous rock land	AcG				
Sheephead rocky fine sandy loam	SpG2	30-65	1.5-4.5 (0-8 inches) (8-51 inches)	 (0.11-0.13) (0.05-0.07)	1.38-4.26 (0.88-1.04) (0.5-3.22)
Tollhouse rocky coarse sandy loam	ToG	30-65	0.5-1.5	0.1-0.12	0.6-2.16

Recharge was calculated for each of the nine bedrock drainage areas for the period 1945 through 2000 using *Recharg2*. For each drainage area, the program was run using input soil moisture capacities of 0.6, 2.16, and 1.38 inches, the minimum, maximum and median, respectively, of the range of soil moisture capacity estimated for the basins. In addition, for each basin, and for each of the soil moisture capacities listed above, the program was run using max runoff values of: 1, 3, 5, 7, 9, 11, 13, 15, 17 and 19 percent to provide a range of results to consider. The program outputs the calculated yearly recharge and runoff. The results for each basin, and for each of the three soil moisture capacities used in the analysis were reduced and evaluated as follows.

For each soil moisture capacity used in the calculation of recharge for each basin, the calculated annual runoff that was output from *Recharg2* was compared to the annual runoff for that basin as estimated in the stream recharge section (above). For each year, the simulation that resulted in a calculated runoff (from *Recharg2*) that most closely agreed with the runoff, as estimated in the stream recharge section (above), was compiled along with that resulting recharge value. The maximum runoff and associated recharge values for each of the sub-basins considered in the bedrock recharge analysis are summarized on a yearly basis for each of the three soil moisture capacities considered (Appendix E). For all basins, regardless of the soil moisture capacity, the average max runoff value required to best match the previously estimated or measured runoff ranged from approximately 9 percent to about 15 or 16 percent. The estimated total average annual bedrock recharge to Borrego Valley ranged from 1,336 af/yr, calculated using a soil moisture capacity of 2.16 inches, to 2,428 af/yr, calculated using a soil moisture capacity of 0.6 inches. The intermediate soil moisture capacity of 1.38 inches is considered the most representative soil moisture capacity used in this evaluation. The estimated average annual bedrock recharge calculated using the soil moisture capacity of 1.38 inches was approximately 1,790 af/yr (Table 9). Annual values of bedrock recharge for each basin, as calculated using the soil moisture capacity of 1.38 inches, are summarized in Table 10. In most years, there is no bedrock recharge in most of the watersheds. Bedrock recharge occurs in most basins only in the wettest years and only after the demands of runoff, PET and soil moisture holding capacities have been satisfied. It is, however, an important source of recharge, averaging 1,790 af/yr more recharge to the Borrego Valley than from stream recharge alone. Estimated annual recharge to bedrock underlying the surrounding watershed was used in the respective annual water budget calculation. No attempt was made to estimate the delay between recharge into the bedrock system and recharge from the bedrock system into the alluvial aquifer.

Table 9. Estimated Average Annual Bedrock Recharge (acre-feet)

Soil Moisture Capacity (inches)		
0.6	1.38	2.16
2,428	1,791	1,336

Table 10. Bedrock Recharge Summary

YEAR	Coyote Mountain	Dry Canyon	Hellhole Canyon	Henderson Canyon	Indian Head Mtn.	Northwest Slopes	Pinyon Ridge	S.Borrego Palm Can.	S.Coyote Canyon	**Totals**
	acre-feet									
1945	0	0	132	0	0	0	0	0	0	132
1946	0	0	583	0	0	0	0	0	0	583
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	1351	0	0	0	0	0	0	1351
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	2166	356	0	0	394	57	0	2973
1953	0	0	629	0	0	0	0	0	0	629
1954	0	0	802	0	0	0	0	0	0	802
1955	0	0	908	0	0	0	0	0	0	908
1956	0	0	0	0	0	0	0	0	0	0
1957	0	0	1464	271	0	0	310	43	0	2088
1958	0	0	1603	0	0	0	0	0	0	1603
1959	0	0	0	0	0	0	0	0	0	0
1960	0	0	503	0	0	0	0	0	0	503
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	2716	462	0	0	497	74	0	3749
1967	0	0	1987	22	0	0	0	5	0	2014
1968	0	0	0	0	0	0	0	0	0	0
1969	0	0	3697	515	0	0	462	83	0	4757
1970	0	0	0	0	0	0	0	0	0	0
1971	0	0	0	0	0	0	0	0	0	0
1972	0	0	0	0	0	0	0	0	0	0
1973	0	0	66	0	0	0	0	0	0	66
1974	285	208	4101	1073	94	248	1451	169	344	7973
1975	0	0	0	0	0	0	0	0	0	0
1976	0	0	702	90	0	0	74	14	0	880
1977	0	0	0	0	0	0	0	0	0	0
1978	507	237	6777	1238	129	331	1432	198	390	11239
1979	0	0	1881	100	0	0	34	16	0	2031
1980	1689	626	8904	2427	386	980	3429	379	1038	19858
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	1226	0	0	0	0	0	0	1226
1984	0	0	0	0	0	0	0	0	0	0
1985	0	0	73	0	0	0	0	0	0	73
1986	0	0	855	0	0	0	0	0	0	855
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	2358	178	0	0	5	30	0	2571
1992	0	65	2087	474	6	24	610	74	105	3445
1993	1986	776	6724	2405	449	1144	3587	375	1287	18733
1994	0	0	0	0	0	0	0	0	0	0
1995	255	199	1789	636	92	241	950	99	329	4590
1996	0	0	0	0	0	0	0	0	0	0
1997	0	0	1464	271	0	0	310	43	0	2088
1998	0	0	1603	0	0	0	0	0	0	1603
1999	0	0	0	0	0	0	0	0	0	0
2000	0	0	503	0	0	0	0	0	0	503
Low	0	0	0	0	0	0	0	0	0	0
Ave	**84**	**38**	**1074**	**188**	**21**	**53**	**242**	**30**	**62**	**1791**
High	1986	776	8904	2427	449	1144	3587	379	1287	19858

Summary of Groundwater Recharge

Sources of recharge considered thus far, underflow, stream recharge and bedrock recharge comprise all sources of natural groundwater recharge to Borrego Valley from the surrounding watershed. However, published water level contour maps and numerical modeling have shown a groundwater divide in the vicinity of San Felipe Creek, and that much of the recharge from San Felipe Creek flows east and southeast towards Ocotillo Wells (Figures 31 and 32) (Henderson, 2001; Moyle, 1982). Therefore, for the purpose of water budget calculations, one half of all recharge from San Felipe Creek was assumed to flow toward Borrego Valley as recharge to the aquifer system, while the remaining recharge from San Felipe Creek was assumed to flow away from Borrego Valley towards Ocotillo Wells. During the period 1945 through 2000, average annual recharge to Borrego Valley was approximately 5,670 af/yr (Table 11). Total annual groundwater recharge to Borrego Valley ranged from approximately 600 acre-feet in 1975 to approximately 46,000 acre-feet in 1980. This extreme range of almost two full orders of magnitude occurred within a time period of only 5 years.

Irrigation Return Flow

Irrigation return flow is a potential source of artificial recharge, although it does not provide any additional water to the aquifer beyond the sources of natural recharge described above. Rather, it is that portion of the water pumped from the aquifer for irrigation purposes that returns to the aquifer via seepage through the vadose zone. Currently, the two most intensive uses of groundwater in Borrego Valley are irrigation for citrus groves and for golf course grass. For these reasons, irrigation return flow was evaluated for both these cases.

Irrigation return flow to groundwater was estimated from a citrus grove and from a golf course fairway in Borrego Valley. A chloride mass balance technique was used for the analysis of irrigation return flow. This technique was selected because the measurement of natural tracers in the environment to estimate recharge has been extensively used in arid and semi-arid regions, and it is a relatively simple analysis to conduct (Allison et al., 1983; Allison et al., 1994, Prudic, 1994; Scanlon, 1991; Sukhija et al., 1987). Chloride occurs naturally in the groundwater that is pumped and used for irrigation in Borrego Valley and, as such, provides a natural tracer that can easily be measured in the irrigation water and in the soil profile in the areas that are being irrigated. In principle, most plant species do not take up significant quantities of chloride from soil water and, therefore, chloride is concentrated

Table 11. Borrego Valley Recharge Summary

YEAR	RECHARGE TO THE BORREGO VALLEY AQUIFER SYSTEM (acre-feet)			
	BEDROCK	STREAM	UNDERFLOW	TOTAL
1945	132	5639	16	5787
1946	583	3436	16	4035
1947	0	1094	16	1110
1948	0	1273	16	1289
1949	1351	2347	16	3714
1950	0	852	16	868
1951	0	3881	16	3897
1952	2973	4885	16	7874
1953	629	2692	16	3337
1954	802	3049	16	3867
1955	908	3000	16	3924
1956	0	2480	16	2496
1957	2088	787	16	2891
1958	1603	3766	16	5385
1959	0	2336	16	2352
1960	503	2318	16	2837
1961	0	2065	16	2081
1962	0	1634	16	1650
1963	0	1914	16	1930
1964	0	1690	16	1706
1965	0	2392	16	2408
1966	3749	2138	16	5903
1967	2014	1969	16	3999
1968	0	1394	16	1410
1969	4757	2394	16	7167
1970	0	1766	16	1782
1971	0	1350	16	1366
1972	0	1345	16	1361
1973	66	949	16	1031
1974	7973	1595	16	9584
1975	0	617	16	633
1976	880	833	16	1729
1977	0	2391	16	2407
1978	11239	3989	16	15244
1979	2031	6682	16	8729
1980	19858	26061	16	45935
1981	0	6128	16	6144
1982	470	6601	16	7087
1983	1226	21160	16	22402
1984	0	6740	16	6756
1985	73	4976	16	5065
1986	855	4265	16	5136
1987	0	3155	16	3171
1988	0	2697	16	2713
1989	0	2006	16	2022
1990	0	1777	16	1793
1991	2571	3501	16	6088
1992	3445	2999	16	6460
1993	18733	16305	16	35054
1994	0	1939	16	1955
1995	4590	7034	16	11640
1996	0	2267	16	2283
1997	2088	2283	16	4387
1998	1603	7291	16	8910
1999	0	2235	16	2251
2000	503	1966	16	2485
Low	0	617	16	633
Average	**1791**	**3863**	**16**	**5670**
High	19858	26061	16	45935

by evapotranspiration in the root zone (Allison et al., 1994). Chloride concentration in soil water should approach some constant value with depth through the root zone, and the ratio between this constant value to the concentration of chloride in the applied irrigation water can be combined with the irrigation rate to estimate the recharge as the result of irrigation return flow to groundwater. The water flux can be estimated from chloride concentration profiles of the soil pore water using the following equation (Prudic, 1994):

$$q_w = C_o P/C$$

where:

q_w = the volumetric water flux (recharge),
C_o = is the chloride concentration in precipitation (in this case in irrigation water)
P = is the annual volume of precipitation per unit area (in this case the irrigation rate)
C = is the chloride concentration in pore water measured below the depth affected by evapotranspiration.

This equation is based on assumed steady, uniform downward flow of water (plug flow) and that chloride moves with water (negligible hydrodynamic dispersion). Other assumptions made with this method are (1) the only source of chloride is from the irrigation water, (2) application of chloride in irrigation water is constant through time, (3) land surface is neither aggrading or degrading, and (4) chloride concentration in pore water below the root zone is in equilibrium with the flux of chloride at land surface. The accuracy of the chloride mass balance technique in estimating recharge rates at a particular location depends on how well the assumptions used in the equations match field conditions (Prudic, 1994).

For this evaluation, the chloride concentration profiles from a citrus grove and a golf course were obtained by taking continuous soil core samples and measuring the chloride concentration in pore water at discrete depth intervals from the core samples. Soil cores were obtained using a Solinst[tm] drive point/drive sample apparatus. The apparatus is used to obtain continuous soil cores by driving 5-foot long, 2-inch O.D., continuous core barrels into the ground using a jackhammer and scaffolding for support of an overhead winch used to extract the driven cores. Continuous soil cores were obtained from under the canopy of three adjacent citrus trees in a grove located northwest of the intersection of DiGiorgio Road and Henderson Canyon Road, and from a fairway on the De Anza Desert Country Club golf course (Figure 49). Cores were driven to depths of approximately 13 to 13.5 feet, which was considered sufficiently deep for results not to be impacted by evapotranspiration in the soil, especially for the golf course where the rooting depth of grass is relatively shallow.

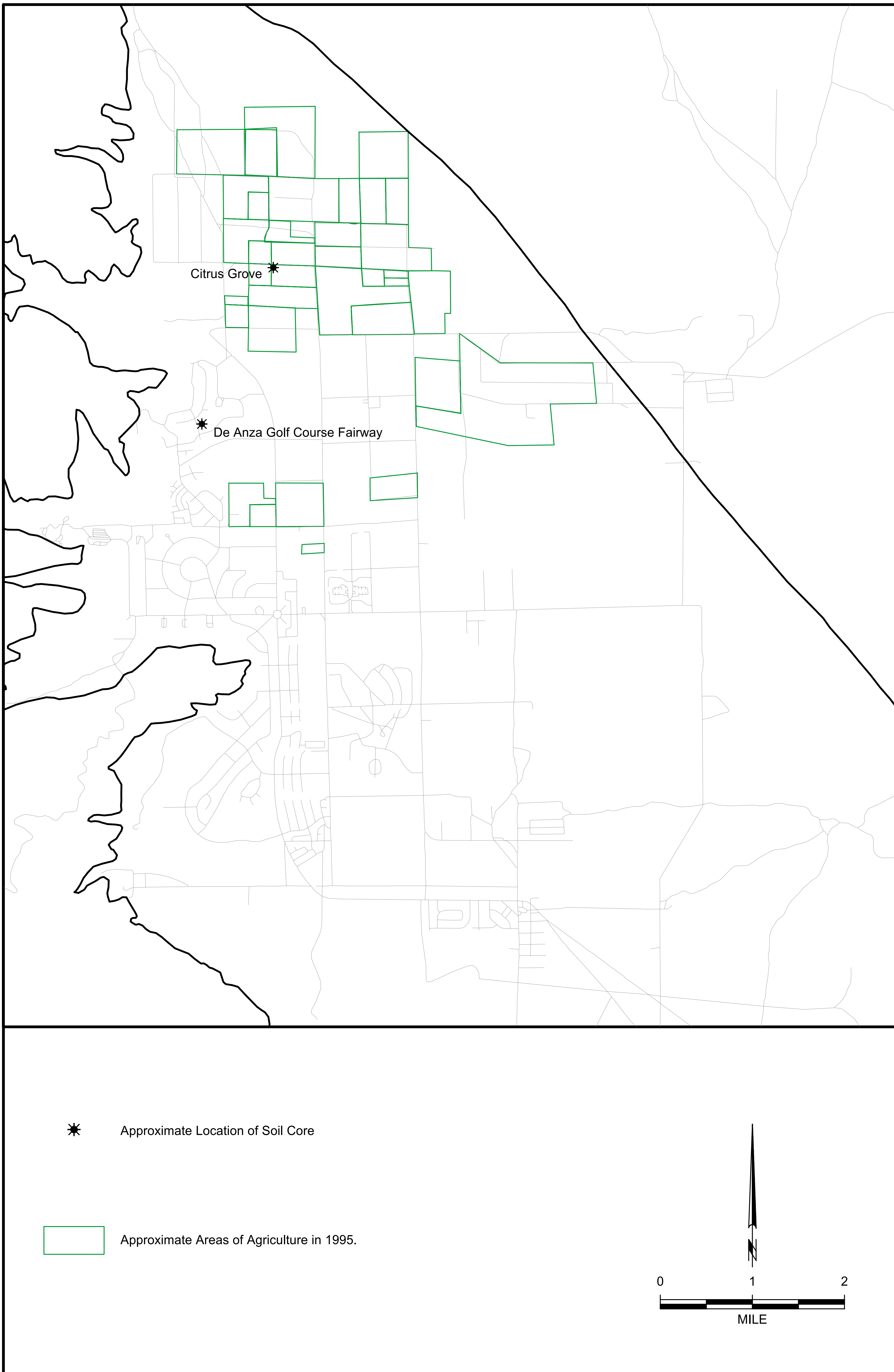


Figure 49. Location of Soil Cores for Chloride Analyis to Estimate Irrigation Efficiency.

As each core barrel was extracted, recovery of soil was determined and the recovered depth intervals were noted. The core was cut into one-foot intervals and each one-foot section of core was immediately capped with either Teflon sheets or laboratory parafilm and plastic end caps. The end caps were secured onto the ends of the core sections with tape wrapped tightly around the core to create the best airtight seal possible. The one-foot sections of core were labeled and placed in dry coolers for transport to the laboratory and storage until analysis.

Once at the San Diego State University (SDSU) hydrogeology laboratory, an approximate 4-centimeter (cm) long ring was cut from the center of each 1-foot core. The exact dimensions of the cut rings were later made to accurately calculate the volume of soil contained in each ring. Gravimetric and volumetric moisture content was determined for each 4-cm long section of soil core by measuring the moist weight and dry weight of each soil sample prior to and after drying, respectively, in an oven at 105^{o}C for at least 24 hours. A de-ionized water extract was collected from each sample and the chloride concentration was measured in the extract using a titrimetric method with mercuric nitrate titrant in accordance with the methods and procedures for this analysis, as outlined in Appendix F. Results from all laboratory analysis of soil samples are tabulated in Appendix F.

A sample of irrigation water from the De Anza Desert Country Club was collected from a sprinkler on the golf course and analyzed at the SDSU hydrogeology laboratory using the same mercuric nitrate titrimetric method. The resulting chloride concentration measured in the golf course irrigation water was 50.6 milligrams per liter (mg/l). A split sample of the golf course irrigation water was delivered along with a sample of the citrus grove irrigation water (collected from a sprinkler under the canopy of a citrus tree) to Ceimic Corporation, San Diego, California (Ceimic), a commercial analytical laboratory. Ceimic utilized a titrimetric method with a silver nitrate titrant for analyses of chloride concentration in the water samples. Ceimic reported the chloride concentration in the split water sample from the golf course (DAGC) at 46 mg/l, which agreed very well with the results from the analysis of the original sample analyzed at SDSU. Ceimic reported the chloride concentration in the water sample from the citrus grove (BVCG) at 69 mg/l (Appendix F).

Estimates of irrigation return flow at the golf course and at the citrus grove were made based on the equation described above. For the citrus grove, the results from all three cores were averaged into one profile (Figure 50). The average pore water chloride concentration in the profile from the citrus grove was approximately 313 mg/l. The average chloride concentration in the profile from the citrus grove and the concentration of chloride

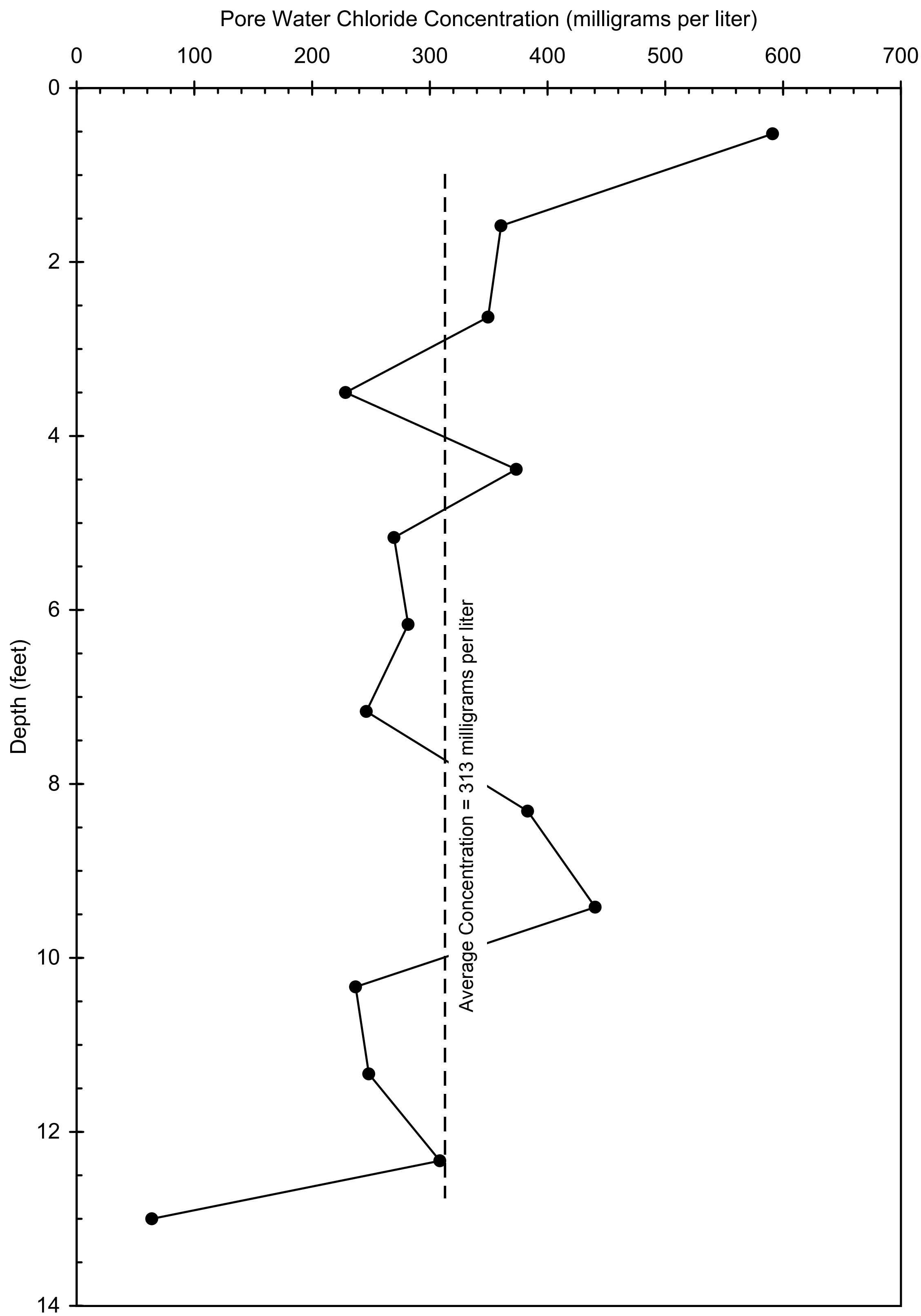


Figure 50. Average Pore Water Chloride Concentration versus Depth, Citrus Grove.

measured in the citrus grove irrigation water sample were used in the above equation to estimate an irrigation return rate in the citrus grove of 22 percent of the applied irrigation rate (Table 12), or approximately 0.72 af/yr per acre (discussed later). For the golf course, the average pore water chloride concentration at depth in the soil profile was approximately 338 mg/l (Figure 51). The average of the two results from analysis of the golf course irrigation water was approximately 48 mg/l. The chloride concentration values for the golf course were used with the equation above to estimate an irrigation return rate on the golf course of 14 percent of the applied irrigation rate (Table 12), or approximately 0.84 af/yr per acre (discussed later). The result of 14 percent irrigation return flow was from a golf course using a wide area broadcast type of water sprinkler, whereas analysis from the citrus orchard, irrigated with a single "micro sprinkler" type of sprinkler under the canopy of each tree, resulted in an estimated 22 percent return flow. The type of irrigation in the citrus grove was considered unique in Borrego Valley to citrus groves and, as such, the estimate of 22 percent return was considered to apply to citrus irrigation only. All other irrigation in Borrego Valley was assumed to generate 14 percent return flow. The irrigation return flow was estimated as described above and used to calculate a net extraction rate for irrigation purposes as discussed in the following sections.

Table 12. Estimated Irrigation Return Flow

Irrigated Area	Chloride Concentration in Applied Water (milligrams per liter)	Average Cloride Concentration in Soil Profile (milligrams per liter)	Estimated Irrigation Return Flow (%)
Citrus Grove	69	313	22
Golf Course Fairway	48	338	14

Sources of Discharge

Prior to 1945, groundwater extraction from the valley was minimal and in 1945 total production of groundwater was estimated to be less than 100 acre-feet (Moyle, 1982). Prior to this time, virtually all discharge from the valley was through the natural processes of evapotranspiration and underflow, and is expected to have been approximately equal to average annual recharge to the valley. Since the late 1940's, groundwater production has been the primary source of discharge from the Borrego Valley aquifer. Groundwater extraction from wells supplies water for all the demands of the valley, principally agricultural, recreational and municipal use. By 1953, agricultural water use had grown to be the main

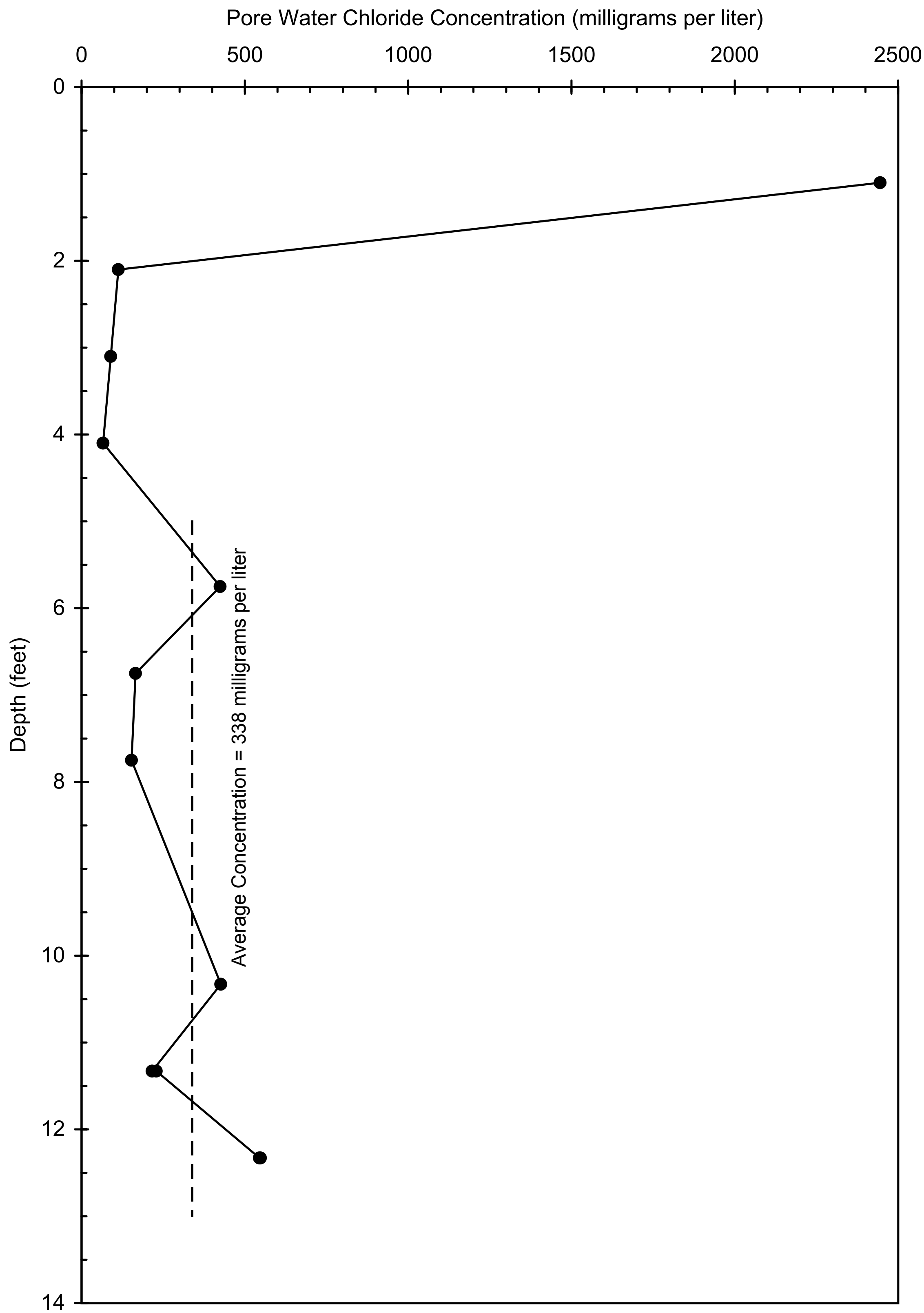


Figure 51. Pore Water Chloride Concentration versus Depth, Golf Course Fairway.

source of discharge from the valley, primarily for the irrigation of table grapes. Recreational water use began in 1953 with irrigation at the De Anza Country Club golf course. Municipal water use in 1953 was relatively small, but growing (Figure 52). Agriculture peaked in the late 1950's and early 1960's, but by the mid 1960's grapes were no longer grown in Borrego Valley and agricultural water use dropped off substantially from the late 1960's to the late 1970's. Since the late 1970s, agriculture has been steadily growing again with citrus as the primary crop in Borrego Valley. Municipal and recreational water use has continued to steadily grow throughout the history of development in Borrego Valley, though increases in recreational water use has been more irregular as new golf courses have been constructed in the valley. Discharge of water by transpiration of phreatophytes and groundwater underflow out of the basin has declined throughout the history of development in Borrego Valley, though it is difficult to quantify without the use of computer models. Groundwater discharge from the basin by transpiration and underflow has been estimated using a numerical groundwater flow model constructed for Borrego Valley, and model estimated discharge due to these sources are summarized in the following sections and are detailed in that report (Henderson, 2001).

Several sources of data were compiled and used to estimate historic groundwater production from Borrego Valley during the period 1945 through 2000. Aerial photographs were reviewed to estimate land use for discrete times during the study period. San Diego County, Department of Planning and Land Use (DPLU), provided access to their aerial photo collections for the years 1953, 1959, 1963, 1968, 1979, and 1992. These photos were examined to determine the area and crop type for agricultural areas. Estimates of net groundwater production required to support the crops were calculated based on the crop area, estimated consumptive use rate, and estimated irrigation return flow. Trends in land use type were generally assumed to increase or decrease linearly between successive photo years. These aerial photos were also used to evaluate the historic coverage of phreatophytes in Borrego Valley. In addition to these photos, a map and inventory of agricultural land use and other groundwater production in 1995 was compiled by a local resident in Borrego Valley and made available for use in this study (Zinser, 1996). Interviews with several farmers, golf course representatives, water municipalities, and other citizens provided additional information relevant to historic land use and estimated consumptive use rates. Groundwater production records were obtained from farmers, golf courses and municipalities, where available. DPLU staff provided additional background regarding historic land use and development plans for Borrego Valley.

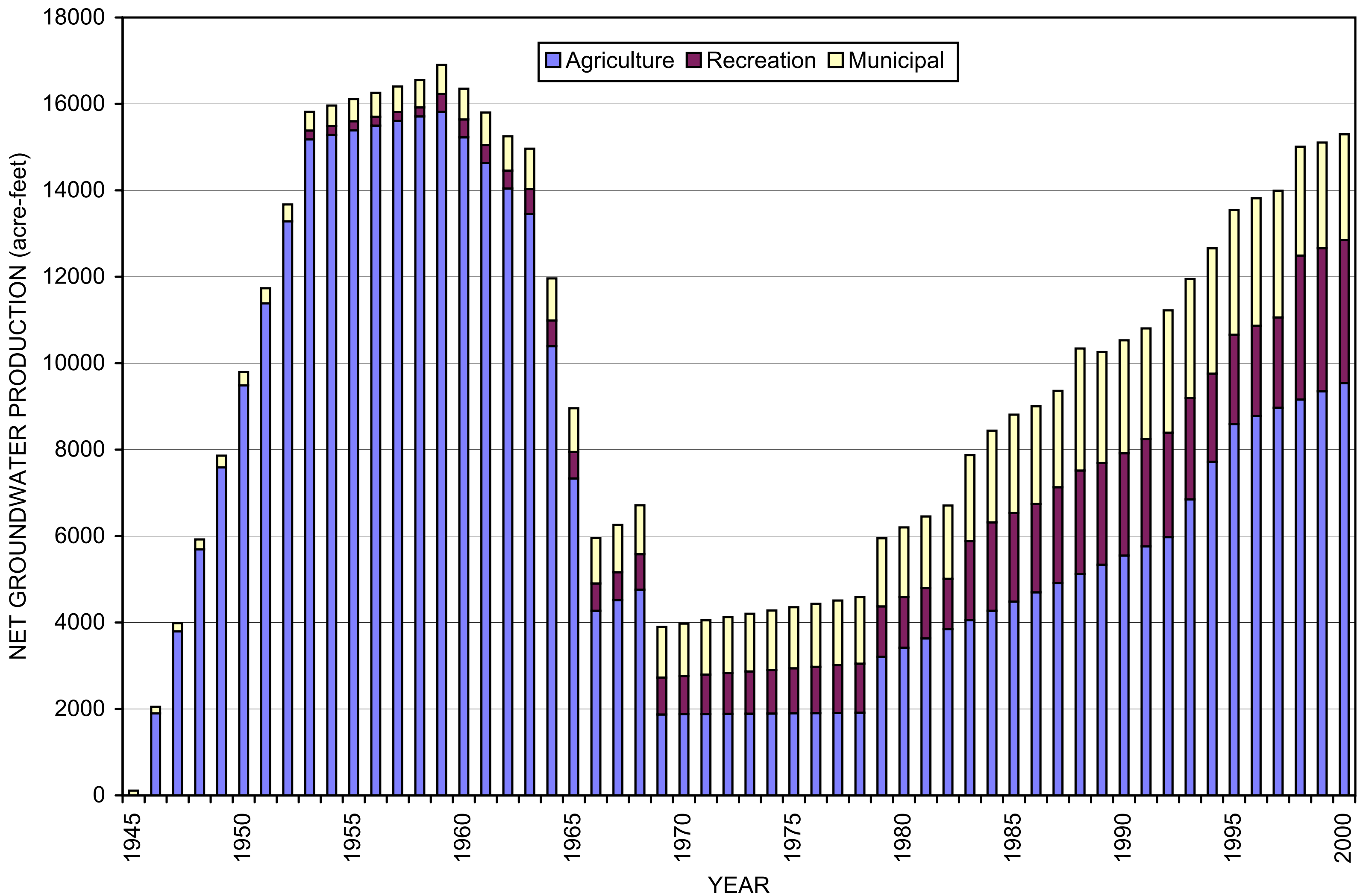


Figure 52. Net Annual Groundwater Production.

Agricultural Water Use

Agricultural water demands have historically been the primary water use in Borrego Valley. Agricultural development rapidly expanded in Borrego Valley after 1945, and is today still the most intensive use of groundwater in the valley. Primary crops grown in the valley have included row crops, table grapes, citrus orchards, and a variety of other agriculture such as date orchards, tree farms and ornamental nurseries, flowers, alfalfa, and potatoes. The principal crop grown in Borrego Valley has shifted from table grapes in the late 1940's through the mid 1960's to citrus, which began to rapidly expand in the late 1970's, and continues today (Table 13). Agricultural groundwater use was estimated using the aerial photos for six discrete times in addition to mapping and inventory of agricultural land use that was compiled for 1995, as well as from personal communications with farmers, DPLU staff and others as mentioned above. Since 1995, several visits to Borrego Valley have been made to monitor agricultural development in the valley. Figures 53 through 58 show the distribution of agricultural land use for the six years with DPLU aerial photo coverage, as interpreted from the aerial photos and what was known of the history of agricultural development in Borrego Valley. Figure 59 shows the distribution of agricultural land as mapped and inventoried in 1995 (Zinser, 1996). For the intervening years, agricultural land use was estimated by interpolating between aerial photo or map years on a crop-by-crop, parcel-by-parcel basis. Estimated agricultural water use for each major crop type is summarized on a yearly basis, based on the photos and land use map, and interpolation (Table 13). Discussions of each of the major crop types historically developed in Borrego Valley and assumptions used to estimate their associated water use follow.

Grape irrigation. Based on the review of aerial photos, interviews with farmers and other residents, and on published literature, table grapes were present and actively irrigated in Borrego Valley during the period since prior to 1951 through 1966 (DPLU; Moyle, 1982). Between 1945 and 1953, table grape irrigation was assumed to increase linearly from zero to the value estimated based on the 1953 aerial photo. Following a labor dispute, table grapes were no longer irrigated in Borrego Valley after 1966 (Moyle, 1982). Gross irrigation demand applied to table grapes in Borrego Valley was estimated to be six feet per year based on rates reported for Coachella and the Imperial-Colorado desert of Southern California (DWR, 1975). Net groundwater extraction values are based on an irrigation efficiency of 86 percent with 14 percent of the gross applied water returning to groundwater as irrigation return flow based on results of the chloride mass balance analysis (above). Net

Table 13. Agricultural Water Use in Borrego Valley

Year	Grapes Area (acres)	Grapes Net Production [14% return] (acre-feet)	Row Crops Area (acres)	Row Crops Net Production [14% return] (acre-feet)	Citrus Area (acres)	Citrus Net Production [22% return] (acre-feet)	Other Area (acres)	Other Net Production [14% return] (acre-feet)	Total Net Agricultural Production (acre-feet)
1945		0		0		0		0	0
1946		1373		508		17		0	1897
1947		2745		1017		33		0	3795
1948		4118		1525		50		0	5692
1949		5490		2033		67		0	7590
1950		6863		2541		83		0	9487
1951		8235		3050		100		0	11385
1952		9608		3558		117		0	13282
1953	2128	10980	2364	4066	53	134	0	0	15180
1954		10993		4142		151		0	15286
1955		11006		4217		169		0	15393
1956		11019		4293		187		0	15499
1957		11032		4368		205		0	15605
1958		11045		4444		223		0	15712
1959	2143	11058	2627	4519	95	241	0	0	15818
1960		10771		4159		294		3	15227
1961		10484		3799		347		5	14636
1962		10197		3439		400		8	14045
1963	1921	9910	1790	3079	178	454	6	11	13454
1964		6607		3317		461		9	10394
1965		3303		3555		469		6	7334
1966	0	0		3793		477		4	4274
1967		0		4031		484		2	4517
1968	0	0	2482	4268	219	492	0	0	4761
1969		0		1377		492		4	1873
1970		0		1377		492		9	1878
1971		0		1377		492		13	1882
1972		0		1377		492		17	1886
1973		0		1377		492		22	1891
1974		0		1377		492		26	1895
1975		0		1377		492		30	1899
1976		0		1377		492		35	1904
1977		0		1377		492		39	1908
1978		0		1377		492		43	1912
1979	0	0	801	1377	1043	1782	18	48	3207
1980		0		1271		1907		242	3420
1981		0		1165		2032		436	3633
1982		0		1059		2157		630	3846
1983		0		953		2282		824	4059
1984		0		847		2407		1018	4272
1985		0		741		2532		1212	4485
1986		0		636		2657		1406	4698
1987		0		530		2781		1600	4911
1988		0		424		2906		1794	5124
1989		0		318		3031		1988	5337
1990		0		212		3156		2182	5550
1991		0		106		3281		2376	5763
1992	0	0	0	0	1593	3406	801	2570	5976
1993		0		0		4147		2701	6848
1994		0		0		4888		2832	7720
1995	0	0	0	0	2587	5630	1723	2963	8593
1996		0		0		5819		2963	8782
1997		0		0		6009		2963	8972
1998		0		0		6198		2963	9161
1999		0		0		6388		2963	9351
2000		0		0	2587	6578		2963	9541

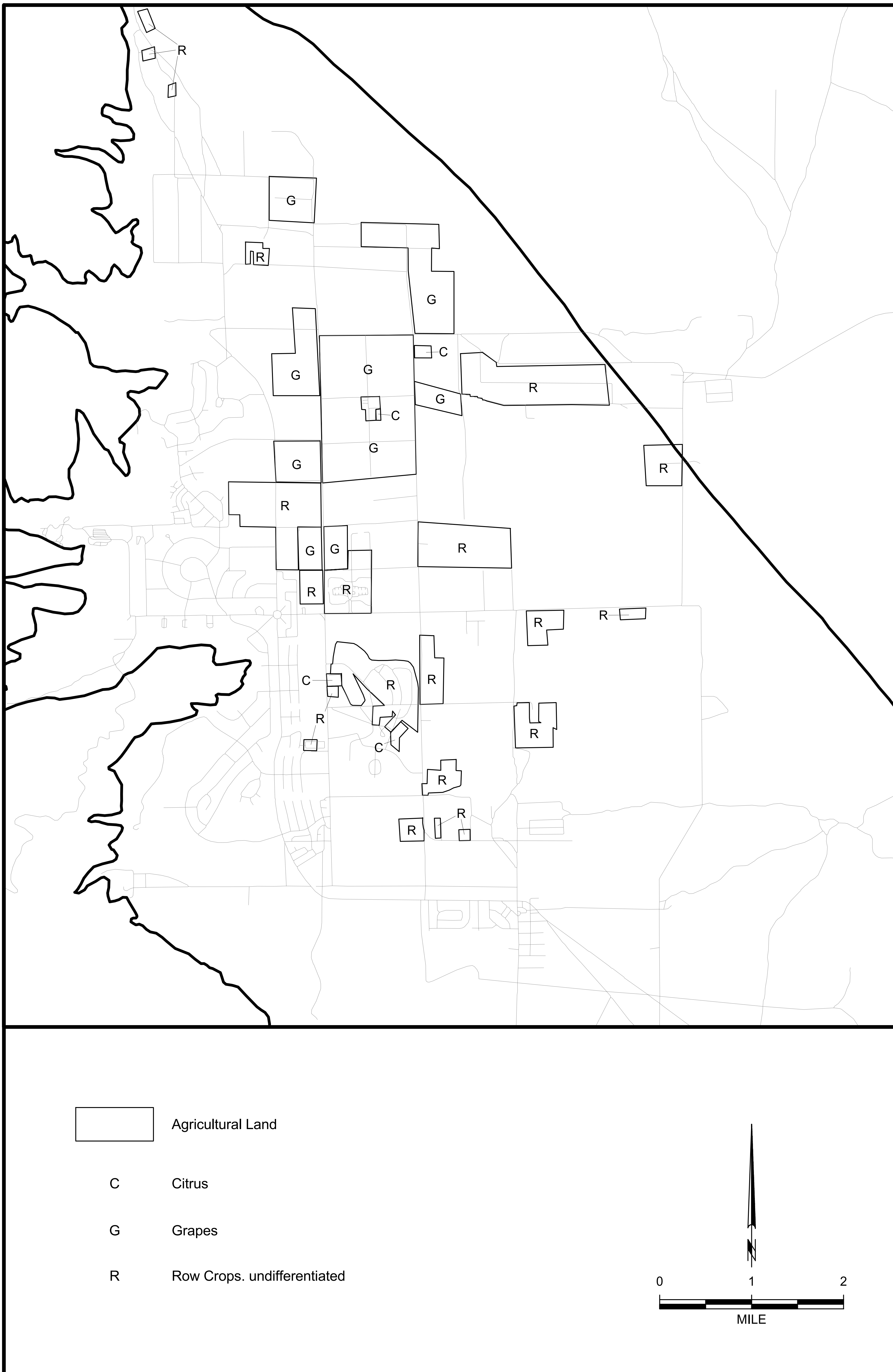


Figure 53. Agricultural Land Use in Borrego Valley, 1953.

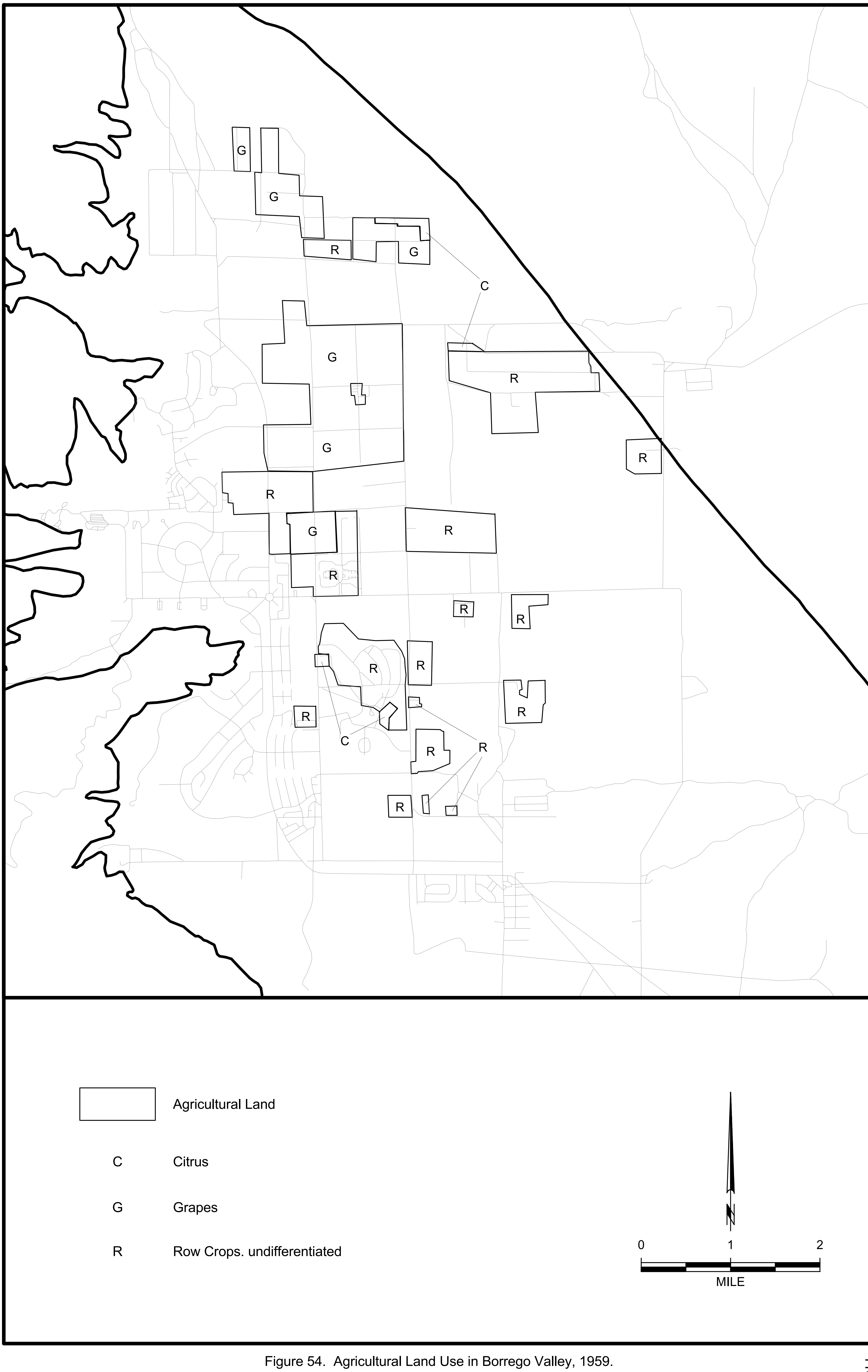


Figure 54. Agricultural Land Use in Borrego Valley, 1959.

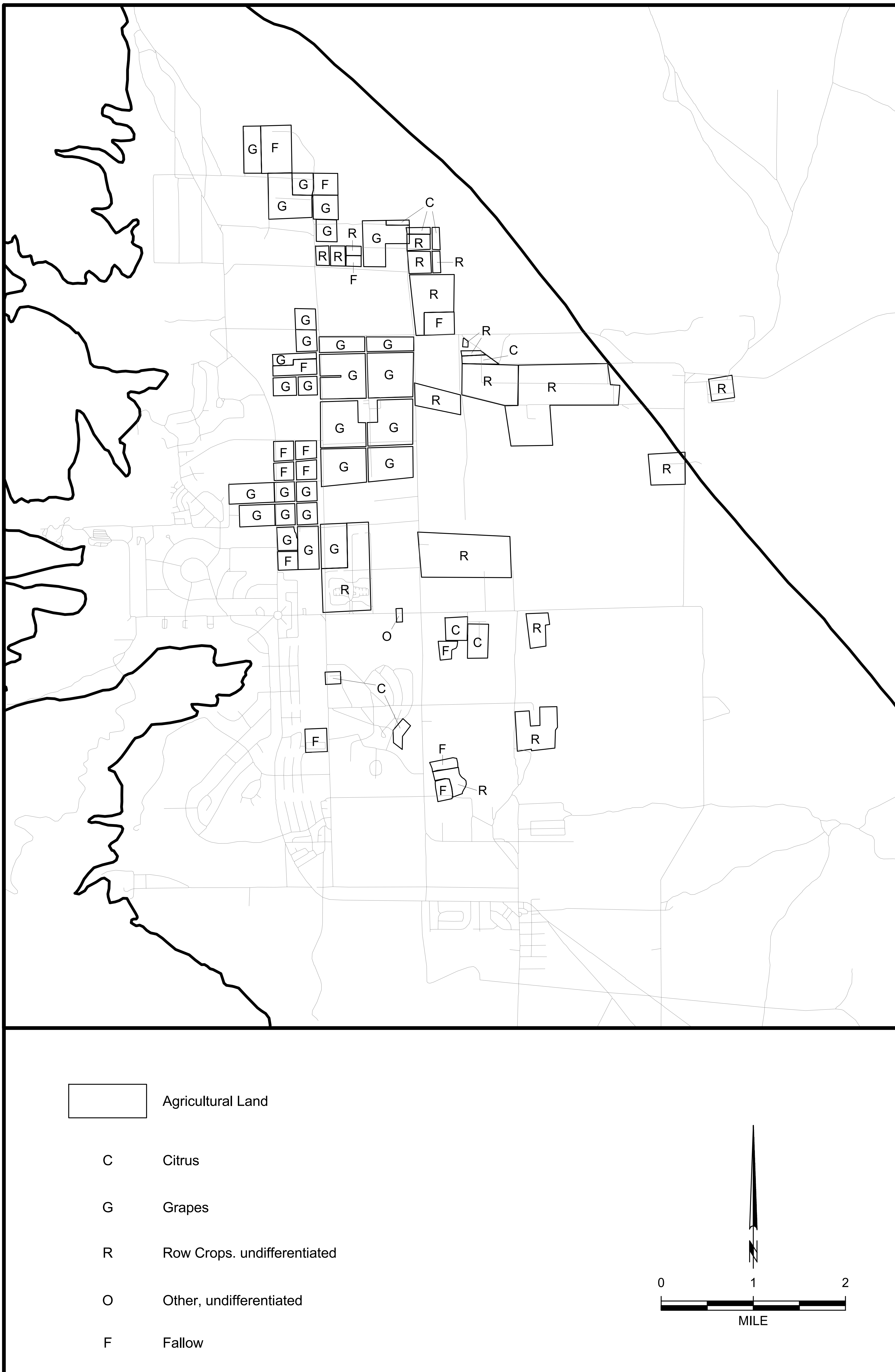


Figure 55. Agricultural Land Use in Borrego Valley, 1963.

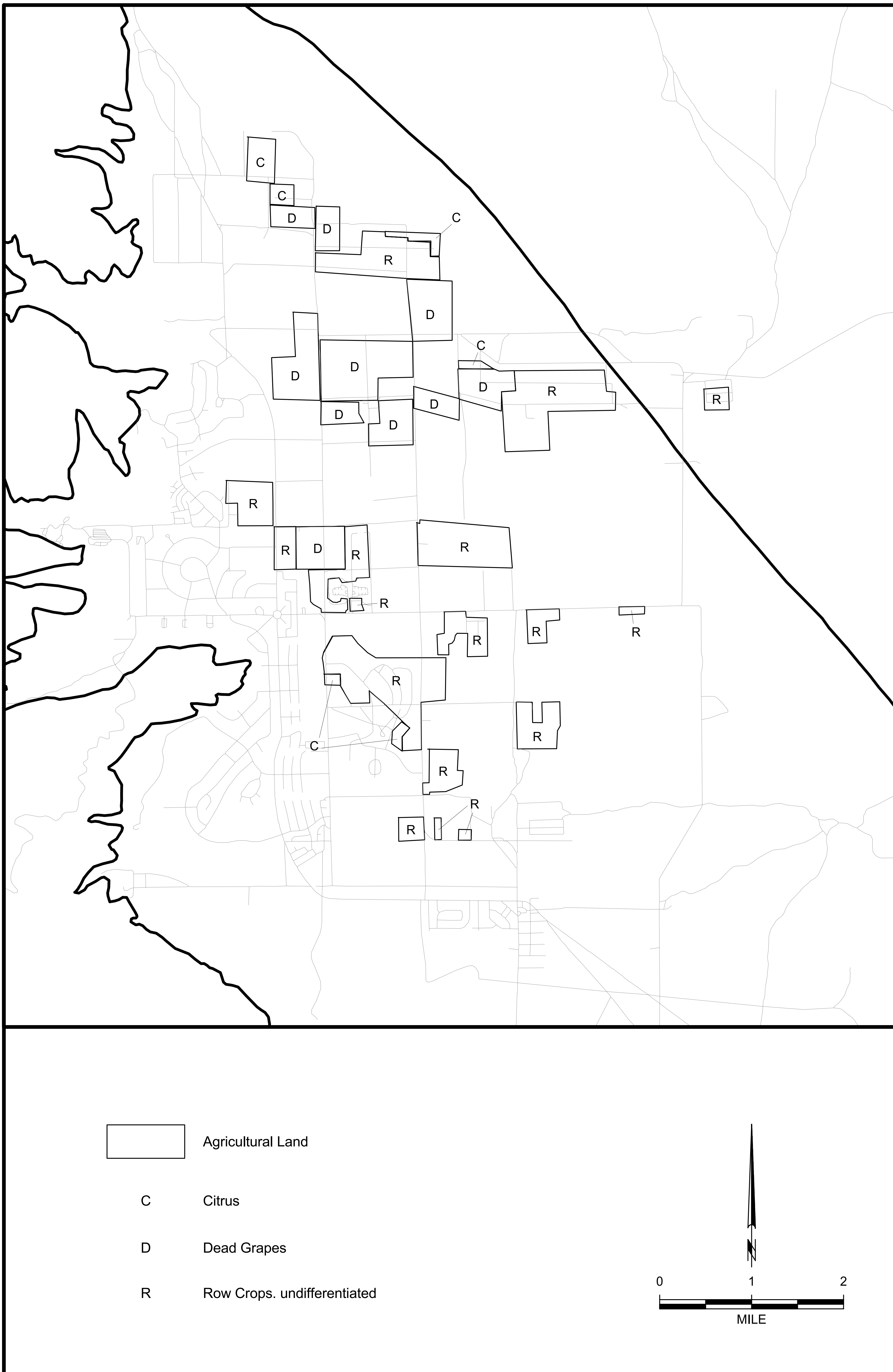


Figure 56. Agricultural Land Use in Borrego Valley, 1968.

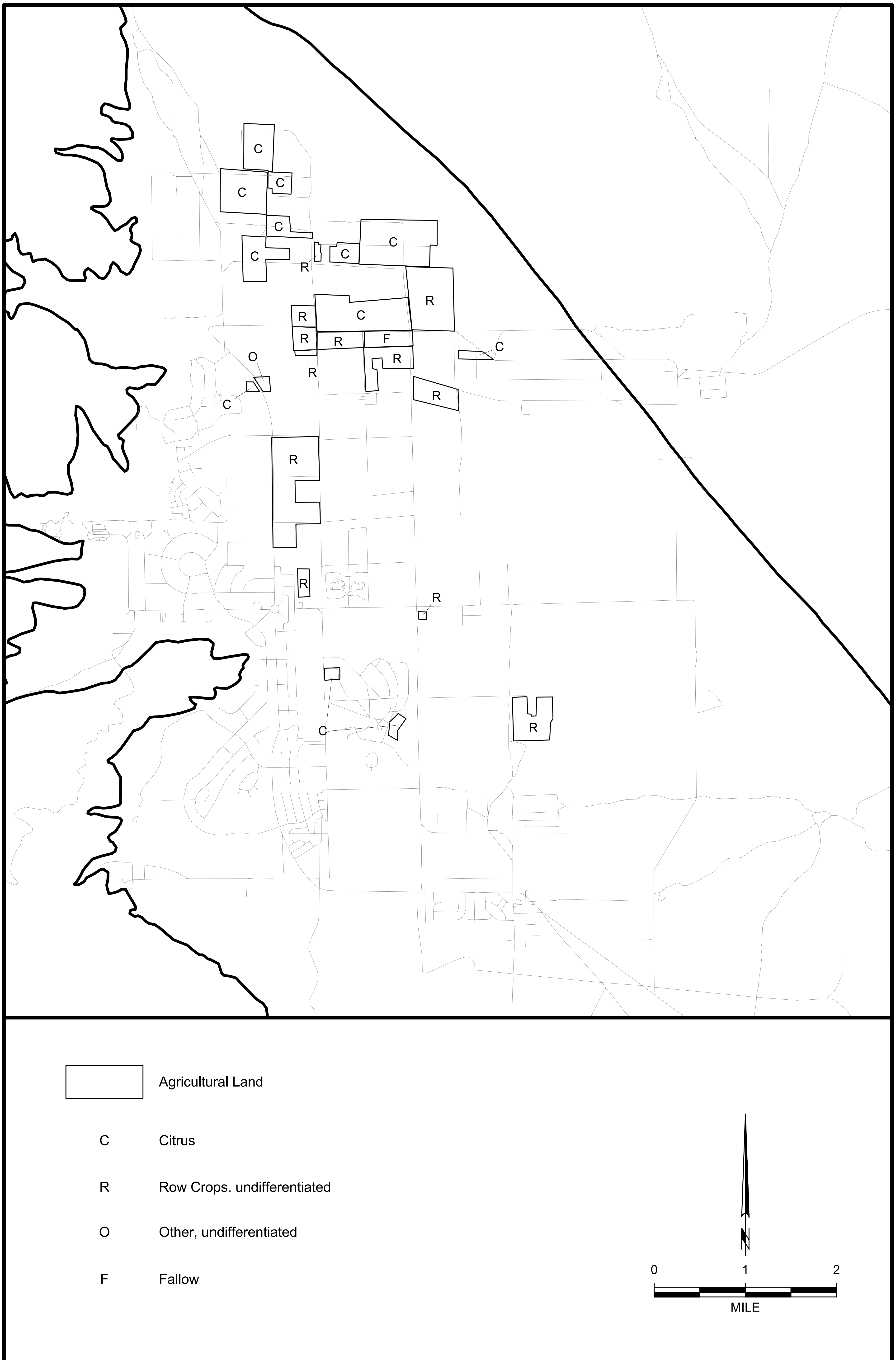


Figure 57. Agricultural Land Use in Borrego Valley, 1979.

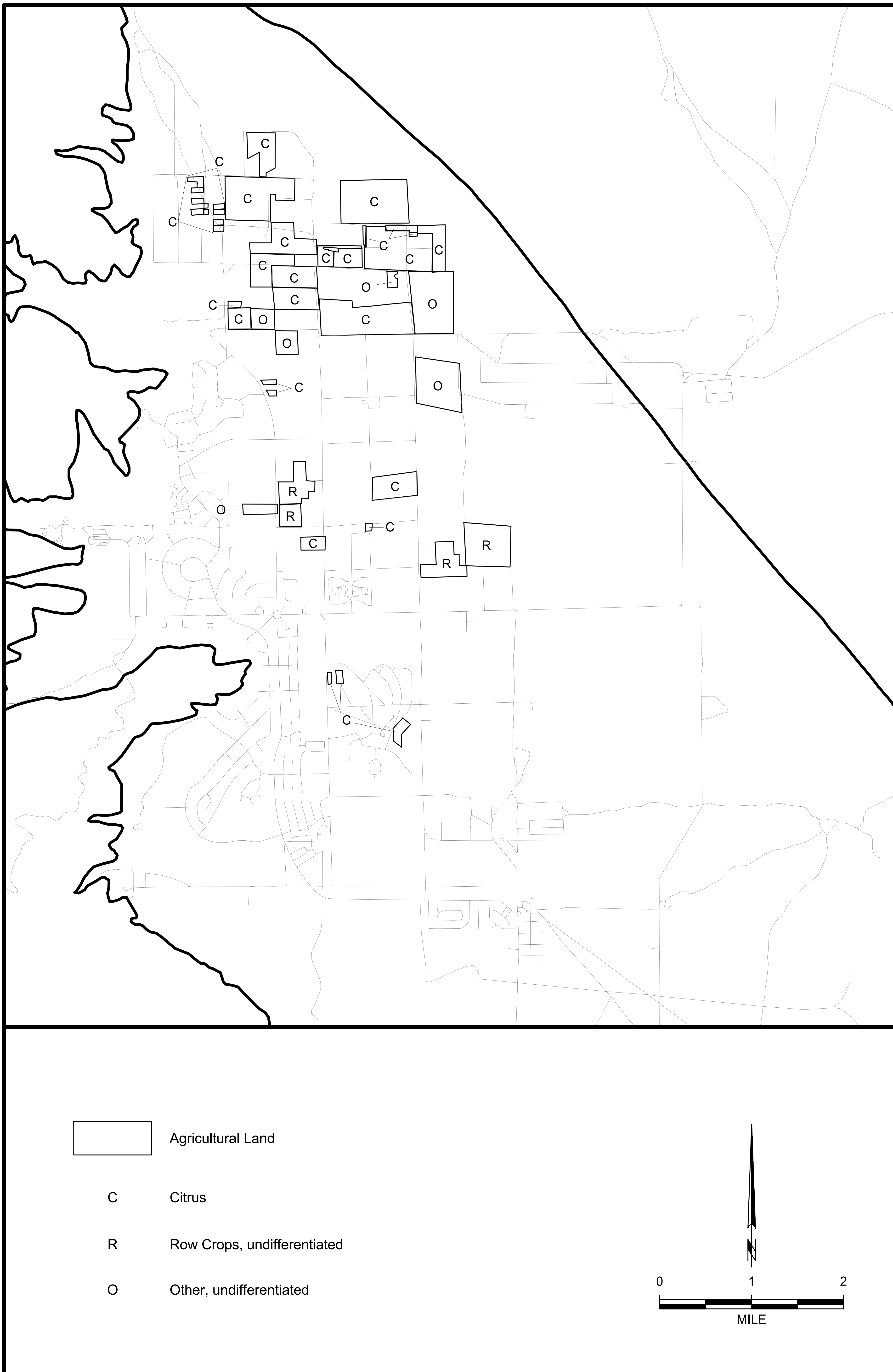
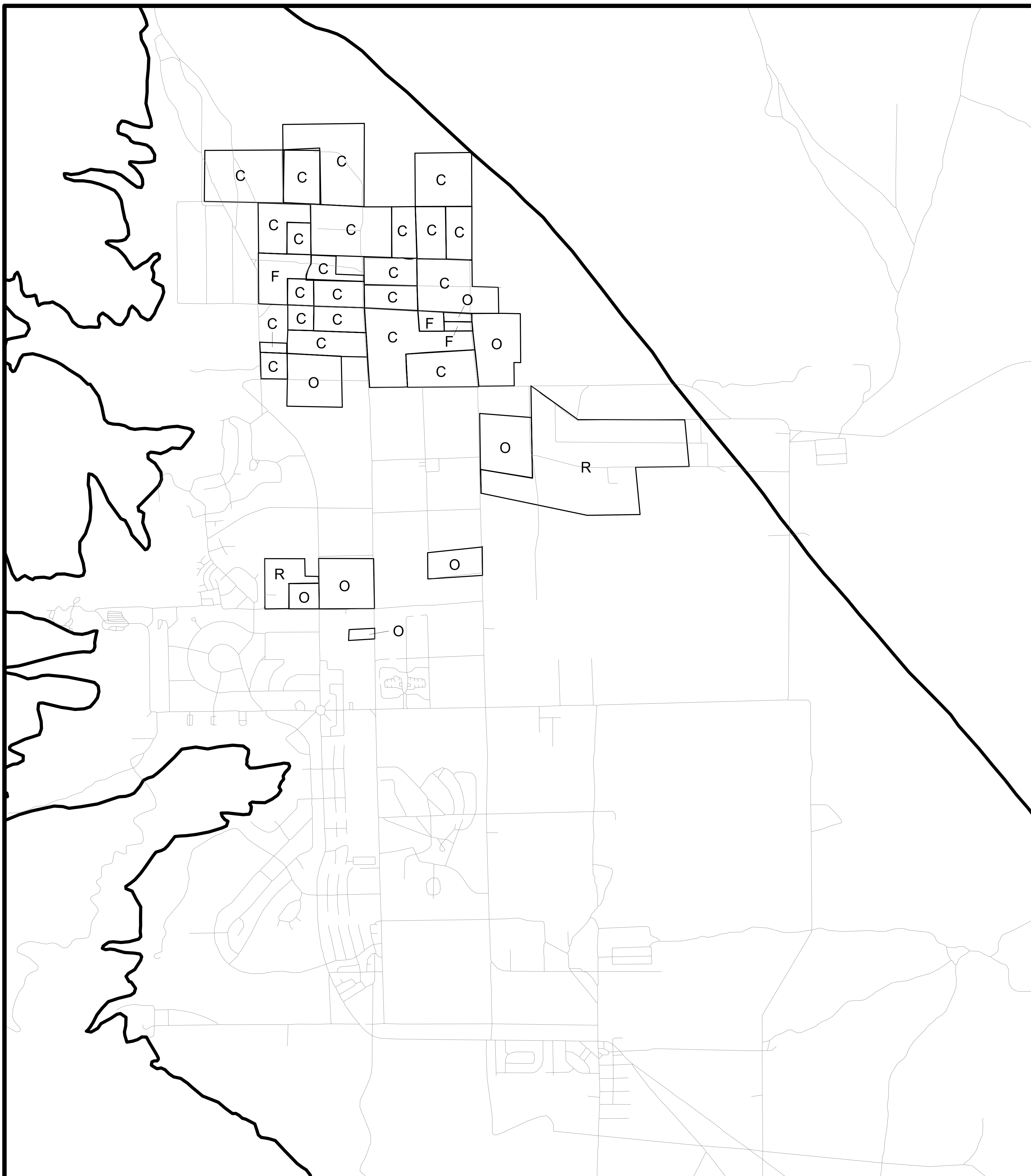


Figure 58. Agricultural Land in Borrego Valley, 1992.



Agricultural Land

C Citrus

R Row Crops. undifferentiated

O Other, undifferentiated

F Fallow

0 1 2
MILE

Figure 59. Agricultural Land in Borrego Valley, 1995.

annual groundwater production in Borrego Valley associated with table grape irrigation is estimated to have ranged from approximately 1,370 acre-feet in 1946 to approximately 11,060 acre-feet in 1959, and declined to zero by 1966 (Table 13).

Row crop irrigation. Based on the review of aerial photos, undifferentiated row crops were present and actively irrigated in Borrego Valley during the period 1953 through 1979. Between 1945 and 1953, the area of irrigated row crops was assumed to increase linearly from zero to approximately 2360 acres in 1953. Row crops remained relatively constant through 1968, when they occupied 2480 acres, but declined to 800 acres by 1979. Row crops were not identified on the 1992 aerial photos. During the period between 1979 and 1992, row crop irrigation was assumed to decrease linearly from 800 acres to zero. Gross irrigation applied to undifferentiated row crops was estimated to be 2 feet per year based on rates reported for various types of row crops (Leeden et al., 1990; Moyle, 1982). Net groundwater extraction values are based on an irrigation efficiency of 86 percent with 14 percent irrigation return flow based on results of the chloride mass balance analysis (above). Net annual groundwater production in Borrego Valley associated with undifferentiated row crop irrigation is estimated to have ranged from approximately 510 acre-feet in 1946 to approximately 4,520 acre-feet in 1959, and declined to zero by 1992 (Table 13).

Citrus irrigation. Based on the review of aerial photos, interviews with farmers and other residents, and on published literature, citrus groves have been present and actively irrigated in Borrego Valley since approximately 1953 (DPLU; Moyle, 1982). Between 1945 and 1953, citrus grove irrigation was assumed to increase linearly from zero to approximately 50 acres. By 1979 citrus had become the primary agricultural product grown in Borrego Valley and has continued as such through 2000, currently occupying approximately 2600 acres. Gross irrigation applied to citrus orchards was estimated to vary from 1 foot per year to 3.26 feet per year based on the maturity of individual citrus orchards and on irrigation rates reported for citrus. The maturity of individual citrus orchards was determined from aerial photos, interviews with farmers and field confirmation. Irrigation rates for young citrus, up to approximately 5 years in age, was reported to be approximately 1 foot per year based on interviews with local farmers (Bauer, 1997; Fortiner, 1997). The irrigation rate for mature citrus was estimated to be approximately 3.25 feet per year based on interviews with local farmers, and rates reported in the literature for citrus in Borrego

Valley, Coachella and the Imperial-Colorado desert of Southern California (DWR, 1975; Bauer, 1997; Fortiner, 1997; Moyle, 1982). Citrus identified as young in 1995 was assumed to have reached maturity by 2000. Net groundwater extraction values are based on an irrigation efficiency of 78 percent with 22 percent irrigation return based on the chloride mass balance analysis (above). Net annual groundwater production in Borrego Valley associated with citrus orchard irrigation is estimated to have ranged from 17 acre-feet in 1946 to over approximately 6,580 acre-feet in 2000 (Table 13).

Irrigation of other agriculture. Based on the review of aerial photographs, interviews with local farmers and residents, and on published sources, a considerable amount of a variety of miscellaneous agriculture was present and irrigated in Borrego Valley during the period from 1963 through 2000. Miscellaneous other agriculture identified predominantly includes ornamental tree farms and nurseries, alfalfa, and potatoes. The gross irrigation applied to ornamental tree farms and nurseries in Borrego Valley was estimated to be approximately 2 feet per year, based on irrigation rates reported for Borrego Valley, Coachella, and the Imperial-Colorado desert of southern California (DWR, 1975; Moyle, 1982). The gross irrigation applied to alfalfa in Borrego Valley was estimated to be 6.2 feet per year, based on reported irrigation rates for alfalfa in Borrego Valley, Coachella, and the Imperial-Colorado desert of southern California (DWR, 1975; Moyle, 1982). Gross irrigation applied to potatoes in Borrego Valley is estimated to be approximately 2 feet per year based on well production records obtained by the DPLU, which is also supported by values in the literature for potatoes in the Southwest (DPLU; Leeden et al., 1990). Estimation of yearly values of net groundwater production to support these crops was based on interpolation between aerial photo years on a crop-by-crop basis. Between 1959 and 1963, irrigation of miscellaneous other crops was assumed to increase linearly from zero to 11 acre-feet in 1963. Net groundwater extraction values are based on an irrigation efficiency of 86 percent with 14 percent irrigation return flow based on results of the chloride mass balance analysis (above). Net annual groundwater production associated with the irrigation of miscellaneous agriculture in Borrego Valley is estimated to have ranged from 3 acre-feet in 1960 to approximately 2,960 acre-feet in 2000 (Table 13).

Recreational Water Use

Recreation has become the second most intensive use of groundwater in Borrego Valley. The primary use of water for recreational activities in Borrego Valley is for irrigation of the several golf courses in the valley. Golf courses in Borrego Valley include the De Anza Country Club, the Borrego Springs Park and Community Services District (BSPCSD) courses, the Rams Hill Development, and the Road Runner Country Club (Figure 60). Unless stated otherwise, the gross irrigation applied across all golf courses is estimated to be approximately 6 feet per year based on interviews with water municipalities, golf course management and DPLU staff (Burzell, 1997; Gorton, 1997; Peterson, 1997). Irrigation efficiencies were assumed for all golf courses to be 86 percent with 14 percent irrigation return, based on results of the chloride mass balance analysis described above. Net annual total groundwater production for all golf courses listed above is estimated to have ranged from approximately 200 acre-feet in 1953 to approximately 3,300 acre-feet in 2000 (Table 14). A discussion of individual golf courses and the assumptions used regarding their irrigation is described in the following sections.

De Anza Country Club. Total applied irrigation at the De Anza Country Club golf course was based on estimates of irrigated areas from aerial photos and on interviews with golf course representatives regarding the development and timing of build out of the golf course (DPLU; Gorton, 1997). The golf course began development in approximately 1953 and apparently did not reach its current build out scale until approximately 1979. Total applied irrigation is estimated to have been approximately 240 af/yr (net approximately 206 af/yr after irrigation return) between 1953 and 1958, and approximately 480 af/yr (net 412 af/yr) between 1959 and 1963. Total irrigation between 1963 and 1979 was assumed to increase linearly from the rate estimated for 1962 to the rate estimated for 1979, reflecting continued development and improvement of the golf course and associated area to the 1979 acreage. Total irrigation was estimated to have been approximately 800 af/yr in 1979 (net 688 af/yr), by which time the golf course had been developed to it’s approximate current size, and has continued at that rate through 2000 (Table 14).

Borrego Springs Park and Community Services District. Since approximately 1963, and continuing through 2000, the BSPCSD has operated one nine-hole golf course that is estimated to receive approximately 190 af/yr (net 163 af/yr) of irrigation water. Beginning in approximately 1998, irrigation of a second course began with construction of a new large 18-hole golf course. The new golf course is comparable in size to the Rams Hill golf course and has more acreage per hole than many of the older courses in Borrego Valley. Total applied irrigation associated with this course has been estimated to be approximately 1000 af/yr (net 860 af/yr) (BWD, 2001; Peterson, 2001). Thus, total

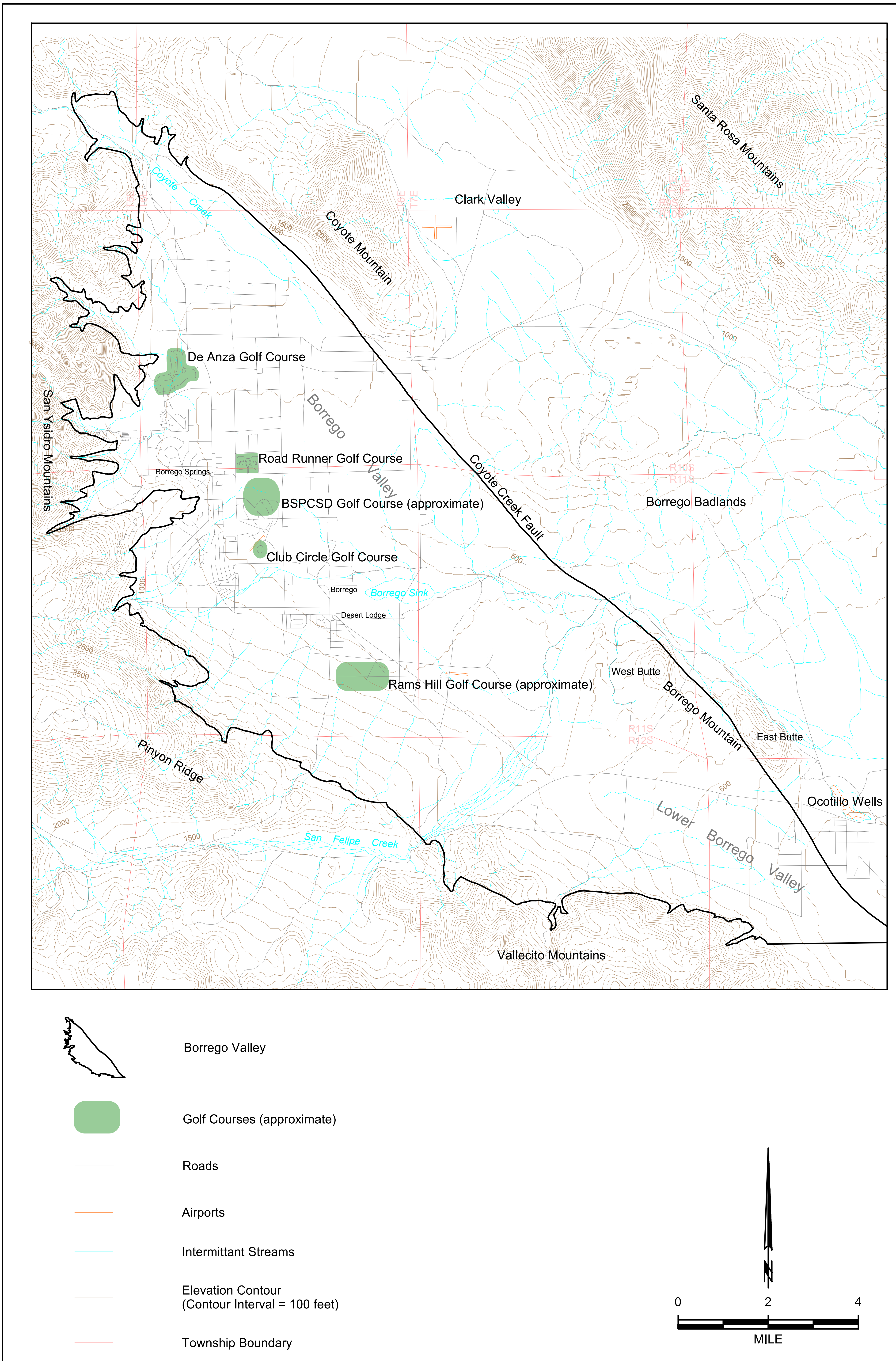


Figure 60. Locations of Golf Courses in Borrego Valley.

Table 14. Recreational Water Use in Borrego Valley

Year	Golf Course Area (acres)			Gross Groundwater Production (acre-feet)				Total Pumped (acre-feet)	Net Production [14% return] (acre-feet)
	De Anza	BSPCSD	Roadrunner	De Anza	BSPCSD	Roadrunner	Ram's Hill		
1945	0	0	0	0	0	0	0	0	0
1946	0	0	0	0	0	0	0	0	0
1947	0	0	0	0	0	0	0	0	0
1948	0	0	0	0	0	0	0	0	0
1949	0	0	0	0	0	0	0	0	0
1950	0	0	0	0	0	0	0	0	0
1951	0	0	0	0	0	0	0	0	0
1952	0	0	0	0	0	0	0	0	0
1953	40	0	0	240	0	0	0	240	206
1954	40	0	0	240	0	0	0	240	206
1955	40	0	0	240	0	0	0	240	206
1956	40	0	0	240	0	0	0	240	206
1957	40	0	0	240	0	0	0	240	206
1958	40	0	0	240	0	0	0	240	206
1959	80	0	0	480	0	0	0	480	413
1960	80	0	0	480	0	0	0	480	413
1961	80	0	0	480	0	0	0	480	413
1962	80	0	0	480	0	0	0	480	413
1963	80	32	0	480	192	0	0	672	578
1964	83	32	0	500	192	0	0	692	595
1965	87	32	0	521	192	0	0	713	613
1966	90	32	0	541	192	0	0	733	630
1967	94	32	0	561	192	0	0	753	648
1968	97	32	30	581	192	180	0	953	820
1969	100	32	33	602	192	197	0	990	851
1970	104	32	36	622	192	213	0	1027	883
1971	107	32	38	642	192	230	0	1064	915
1972	110	32	41	662	192	246	0	1100	946
1973	114	32	44	683	192	263	0	1137	978
1974	117	32	47	703	192	279	0	1174	1009
1975	121	32	49	723	192	296	0	1211	1041
1976	124	32	52	743	192	312	0	1247	1073
1977	127	32	55	764	192	329	0	1284	1104
1978	131	32	58	784	192	345	0	1321	1136
1979	134	32	60	804	192	360	0	1356	1166
1980	134	32	60	804	192	360	0	1356	1166
1981	134	32	60	804	192	360	0	1356	1166
1982	134	32	60	804	192	360	0	1356	1166
1983	134	32	60	804	192	360	769	2125	1827
1984	134	32	60	804	192	360	1025	2381	2048
1985	134	32	60	804	192	360	1025	2381	2048
1986	134	32	60	804	192	360	1025	2381	2048
1987	134	32	60	804	192	360	1225	2581	2220
1988	134	32	60	804	192	360	1425	2781	2392
1989	134	32	60	804	192	360	1380	2736	2353
1990	134	32	60	804	192	360	1396	2752	2367
1991	134	32	60	804	192	360	1531	2887	2483
1992	134	32	60	804	192	360	1453	2809	2416
1993	134	32	60	804	192	360	1376	2732	2350
1994	134	32	60	804	192	360	1016	2372	2040
1995	134	32	60	804	192	360	1050	2406	2069
1996	134	32	60	804	192	360	1072	2428	2088
1997	134	32	60	804	192	360	1072	2428	2088
1998	134	Additional	60	804	1192	360	1516	3872	3330
1999	134	18 hole	60	804	1192	360	1494	3850	3311
2000	134	course	60	804	1192	360	1494	3850	3311

Note: BSPCSD = Borrego Springs Park and Community Services District.

combined irrigation for both of the BSPCSD courses is estimated to be approximately 1,200 af/yr (net 1032 af/yr) (Table 14).

Rams Hill. Construction of the Rams Hill golf course was completed in 1983. The Borrego Water District (BWD) provides groundwater to the Rams Hill Development. The BWD extracts groundwater from approximately seven wells to supply the recreational and municipal water demands of the development. Water production records were obtained from the BWD including the record of water diverted for irrigation purposes at Rams Hill (described below). Total irrigation for the Rams Hill Development has ranged from 1,016 acre-feet in 1994 to 1,531 acre-feet in 1991 (net range from 874 acre-feet to 1,316 acre-feet) and has averaged approximately 1,240 af/yr (net 1,066 acre-feet) for the period 1984 through 2000 (Table 14).

Roadrunner Country Club. Total applied irrigation at the Roadrunner Country Club golf course was based on estimates of irrigated areas from aerial photos and on interviews with golf course representatives regarding the development and timing of build out of the golf course (DPLU; Slade, 1997). The golf course began development in approximately 1967 and apparently did not reach its current build out scale until approximately 1979. Total applied irrigation between 1967 and 1979 was assumed to increase linearly from zero to the rate estimated for 1979, reflecting continued development and improvement of the golf course and associated area to the 1979 acreage. Total irrigation was estimated to have been approximately 360 acre-feet in 1979 (net 310 acre-feet after irrigation return), by which time the golf course had been developed to it's approximate current size, and has continued at that rate through 2000 (Table 14).

Municipal Water Use

Historically, municipal use has been a relatively small but growing component of the total groundwater use in Borrego Valley, based on relatively slow but continuous population growth and related development (Figure 52). Several districts provide water to meet the municipal demand in the valley, including the BWD, the former Borrego Springs Water Company (BSWCo) (which has recently been acquired or whose service area has been annexed by the BWD), the BSPCSD, and the Borrego Air Ranch. Municipal water use has been compiled for the period 1945 through 2000 from production records, where available, and estimates of water use based on interviews with local water municipality representatives, local residents, and DPLU staff. Total municipal demand is estimated to have ranged from approximately 100 acre-feet in 1945 to approximately 2,950 acre-feet in 1996 and was estimated to be approximately 2,450 acre-feet in 2000 (Table 15).

According to BWD personnel, municipal wastewater in Borrego Valley is treated and placed in percolation/evaporation ponds. Return of municipal wastewater as recharge to groundwater has not been considered in previous water budgets and is generally considered negligible, though no estimates of percolation from the treatment ponds are known to have been made (BWD, 2001; Peterson, 2001). According to the DPLU, the BWD wastewater treatment plant was designed to reclaim water for irrigation use. However, in practice the BWD had never been able to produce any reclaimed water, supposedly due to the high evaporation rates from the wastewater ponds (Peterson, 2001). Based on this information, it was assumed for the purposes of this water budget that all of the municipal water was consumptive use with no return flow to groundwater.

A discussion of the production records and assumptions made regarding each of these municipalities follows in the next sections.

Borrego Water District. The Borrego Water District supplies water for all the municipal and recreational demands of the Rams Hill Development. The Rams Hill development was completed in 1983. Complete records for all groundwater production from the BWD wells have been obtained through 1999, including a nearly complete record of water diverted for all irrigation of the golf course and other landscaping. The record for diversion of irrigation water in 1997 was missing and was assumed to be equal to the amount of water diverted for irrigation in 1996. BWDs total groundwater extraction for 2000 was assumed equal to the total production in 1999. Total BWD groundwater production has ranged from approximately 1,360 acre-feet in 1984 to more than 2,300 acre-feet in 1984, and was approximately 1,900 acre-feet in 1999. The fraction of BWDs total production that is used for municipal purposes alone range from approximately 336 acre-feet in 1984 to approximately 890 acre-feet in 1988, and was approximately 420 acre-feet in 1999 (Tables 14 and 15). The BWD has recently acquired or annexed the service area of the former BSWCo. Production from the former BSWCo wells is discussed in the next section.

Borrego Springs Water Company. The Borrego Springs Water Company has supplied water to the majority of the city of Borrego Springs commercial and residential areas. Nearly complete records for all groundwater production from the BSWCo wells have been obtained for the period 1983 through 1999. The production records for 1996 and 1997 were incomplete and production rates for those years were assumed to be equal to the

Table 15. Municipal Water Use in Borrego Valley

Year	Borrego Springs Water Company								Borrego Water District								BSP CSD	BAR	Total Muni Use
	Well 2	Well 3	Well 4	Well 5	Well 10	Well 18	Well 11	Total	Well 1	Well 2	Well 8	Well 10	Well 12	Well 16	ID 3 Wells	Total			
1945	27	13	29			31		100										10	110
1946	38	19	40			43		140										10	150
1947	49	24	52			56		180										10	190
1948	60	29	64			68		221										10	231
1949	71	35	75			80		261										10	271
1950	82	40	87			93		301										10	311
1951	92	45	98			105		341										10	351
1952	103	51	110			118		381										10	391
1953	114	56	122			130		421										10	431
1954	125	61	133			142		462										10	472
1955	136	66	145			155		502										10	512
1956	147	72	156			167		542										10	552
1957	158	77	168			179		582										10	592
1958	169	82	180			192		622										10	632
1959	179	88	191			204		663										10	673
1960	190	93	203			217		703										10	713
1961	201	98	214			229		743										10	753
1962	212	104	226			241		783										10	793
1963	223	109	237			254		823									100	10	933
1964	234	114	249			266		864									100	10	974
1965	245	120	261			279		904									100	10	1014
1966	256	125	272			291		944									100	10	1054
1967	267	130	284			303		984									100	10	1094
1968	277	136	295			316		1024									100	10	1134
1969	288	141	307			328		1064									100	10	1174
1970	299	146	319			340		1105									100	10	1215
1971	310	152	330			353		1145									100	10	1255
1972	321	157	342			365		1185									100	10	1295
1973	332	162	353			378		1225									100	10	1335
1974	343	168	365			390		1265									100	10	1375
1975	354	173	377			402		1306									100	10	1416
1976	364	178	388			415		1346									100	10	1456
1977	375	184	400			427		1386									100	10	1496
1978	386	189	411			440		1426									100	10	1536
1979	397	194	423			452		1466									100	10	1576
1980	408	200	435			464		1506									100	10	1616
1981	419	205	446			477		1547									100	10	1657
1982	430	210	458			489		1587									100	10	1697
1983	441	216	469			501		1627	38	48	450	695			130	252	100	10	1989
1984	387	270	494			525		1675	38	48	450	695			130	336	100	10	2121
1985	391	272	498			529		1690	1	35	407	601	317		141	478	100	10	2278
1986	393	274	501			532		1700	0	0	388	579	354		153	449	100	10	2259
1987	328	325	516			545		1713	100	75	338	657	318		144	406	100	10	2229
1988	294	658	542	43		289		1826	169	88	375	784	756		144	890	100	10	2826
1989	238	549	495	256		371		1909	223	105	333	329	794		144	549	100	10	2568
1990	222	822	547	173	20	126		1909	86	62	306	451	942		144	595	100	10	2614
1991	254	505	504	15	144	408		1828	64	64	373	544	961	7	140	623	100	10	2561
1992	334	475	466	54	202	685		2216	232	4	153	25	570	974	0	505	100	10	2831
1993	267	411	447	40	219	677		2062	126	0	46	81	556	1145	0	578	100	10	2750
1994	367	385	491	4	213	617		2077	169	0	39	25	523	972	0	711	100	10	2898
1995	312	435	623	26	199	406	82	2084	4	19	34	56	557	1073	0	692	100	10	2886
1996	312	435	623	26	199	406	82	2084	25	15	3	102	652	1028	0	753	100	10	2947
1997	312	435	623	26	199	406	82	2084	37	27	74	120	578	977	0	740	100	10	2934
1998	296	413	591	25	188	385	78	1978	21	21	41	88	723	1055	0	433	100	10	2521
1999	287	399	572	24	182	373	75	1914	31	34	55	137	732	925	0	420	100	10	2444
2000	287	399	572	24	182	373	75	1914	31	34	55	137	732	925	0	420	100	10	2444

Notes: All production values are in units of acre-feet.
BSPCSD = Borrego Springs Park and Community Services District.
BAR = Borrego Air Ranch

amount of groundwater produced by the BSWCo in 1995. BSWCo total groundwater extraction for 2000 was assumed equal to the total production in 1999. BSWCo records were not available for production prior to 1983. For the period 1945 through 1983, total groundwater production from BSWCo wells was assumed to increase linearly from 0 to 1,627 acre-feet in 1983. During the period of records that were obtained, groundwater production from the former BSWCo ranged from 1,627 acre-feet in 1983 to 2,216 acre-feet in 1992, and was 1,914 in 1999 (Table 15).

Borrego Springs Park and Community Serves District. The BSPCSD has been in operation since 1963 and provides water to its service area to meet the municipal demand, and supply irrigation water for its golf courses (discussed above). Groundwater production records for the BSPCSD were not available. Groundwater production to satisfy the municipal demand of the BSPCSD was estimated by the BWD to be 75 af/yr, and by a resident engineer in the BSPCSD to be approximately 100 af/yr (Zinser, 1997). A groundwater production rate of 100 af/yr was assumed for the BSPCSD for the entire period 1963 though 2000 (Table 15).

Borrego Air Ranch. A small fraction of the historic municipal demand in Borrego Valley has been at the Borrego Air Ranch. The Borrego Air Ranch is a small community of homes alongside an airstrip to the southeast of the town of Borrego (Figure 2). Groundwater production records for wells at the Borrego Air Ranch were not available. Groundwater production to satisfy the municipal demands of the Borrego Air Ranch has been estimated to be approximately 10 af/yr (BWD, 2001). A groundwater production rate of 10 af/yr was assumed for the Borrego Air Ranch for the entire period 1945 though 2000 (Table 15).

Summary of Groundwater Production

Groundwater production in Borrego Valley has been primarily to satisfy the agricultural, recreational and municipal water demands in the valley. Net total groundwater production has ranged from approximately 100 acre-feet in 1945 to approximately 17,000 acre-feet in 1959, and was approximately 15,000 acre-feet in 2000 (Table 16). In 2000, an estimated 62 percent of the total water use was for agricultural demands, 22 percent for recreational demands and 16 percent for municipal demands (Figure 52).

Table 16. Net Total Groundwater Production in Borrego Valley

Year	Net Agricultural (acre-feet)	Net Recreational (acre-feet)	Municipal (acre-feet)	Net Total Production (acre-feet)
1945	0	0	110	110
1946	1897	0	150	2048
1947	3795	0	190	3985
1948	5692	0	231	5923
1949	7590	0	271	7861
1950	9487	0	311	9798
1951	11385	0	351	11736
1952	13282	0	391	13674
1953	15180	206	431	15818
1954	15286	206	472	15964
1955	15393	206	512	16111
1956	15499	206	552	16257
1957	15605	206	592	16404
1958	15712	206	632	16550
1959	15818	413	673	16903
1960	15227	413	713	16352
1961	14636	413	753	15801
1962	14045	413	793	15251
1963	13454	578	933	14965
1964	10394	595	974	11962
1965	7334	613	1014	8960
1966	4274	630	1054	5958
1967	4517	648	1094	6259
1968	4761	820	1134	6715
1969	1873	851	1174	3899
1970	1878	883	1215	3975
1971	1882	915	1255	4052
1972	1886	946	1295	4128
1973	1891	978	1335	4204
1974	1895	1009	1375	4280
1975	1899	1041	1416	4356
1976	1904	1073	1456	4432
1977	1908	1104	1496	4508
1978	1912	1136	1536	4584
1979	3207	1166	1576	5949
1980	3420	1166	1616	6202
1981	3633	1166	1657	6455
1982	3846	1166	1697	6709
1983	4059	1827	1989	7875
1984	4272	2048	2121	8440
1985	4485	2048	2278	8810
1986	4698	2048	2259	9004
1987	4911	2220	2229	9359
1988	5124	2392	2826	10341
1989	5337	2353	2568	10258
1990	5550	2367	2614	10531
1991	5763	2483	2561	10807
1992	5976	2416	2831	11223
1993	6848	2350	2750	11948
1994	7720	2040	2898	12658
1995	8593	2069	2886	13548
1996	8782	2088	2947	13817
1997	8972	2088	2934	13994
1998	9161	3330	2521	15012
1999	9351	3311	2444	15106
2000	9541	3311	2444	15296

Net Water Budget

Estimated recharge to Borrego Valley was compared to the net total groundwater extraction from wells in Borrego Valley to evaluate the historical overdraft or surplus of the aquifer system. Previous work indicates most, if not all, recharge along San Felipe Creek flows through the alluvium to the east and southeast toward Ocotillo Wells from where San Felipe Creek emerges into the valley (discussed above) (Moyle, 1982). The Palm Spring Formation is shallow in the area between San Felipe Creek and the principle areas of the aquifer, and behaves somewhat as a natural barrier to groundwater flow. In a recent report from their technical committee, the BWD did not include any contribution from San Felipe Creek in their estimates of average recharge to the Borrego Valley aquifer (BWD, 2001). However, numerical modeling based on the new conceptualization of the aquifer system has shown diverging flow from the recharge area of San Felipe Creek, with some flow towards Borrego Valley, and some towards Ocotillo Wells (Henderson, 2001). For these reasons, as previously discussed, one half of all recharge along San Felipe Creek, including stream recharge from Upper- Lower- and East-San Felipe Creek, as well as the underflow along San Felipe Creek, is assumed to recharge the Borrego Valley aquifer. The exclusion of one half of the total recharge calculated for San Felipe Creek represents an average of less than 640 af/yr.

Average annual recharge to the Borrego Valley aquifer is estimated to be approximately 5,670 af/yr. During the period 1945 to 2000, estimated annual groundwater recharge to the aquifer has ranged from approximately 500 acre-feet to approximately 46,000 acre-feet (Table 17). Estimated annual net groundwater extraction has ranged from approximately 100 acre-feet to approximately 17,000 acre-feet, averaging approximately 9,800 af/yr. During the period between 1945 and 2000 it is estimated that groundwater extraction has exceeded recharge by an average of approximately 4,100 af/yr, representing a net loss to the aquifer, due to groundwater extraction alone, of approximately 230,000 acre-feet. This value does not consider additional water lost from the aquifer during this period from natural discharge due to underflow out of the valley and transpiration of phreatophytes. Based on numerical modeling, discharge due to PET and underflow out of the basin during the period from 1945 to 2000 has ranged from approximately 10,000 acre-feet in 1946 to approximately 2,900 acre-feet in 2000, and has averaged approximately 5,100 acre-feet per year (Henderson, 2001). Considering natural discharge from the aquifer during this period, as well as net total extraction, the Borrego Valley aquifer has been

Table 17. Net Water Budget

Year	Recharge				Total Groundwater Extraction	Net Difference [Recharge-Extracted]
	Stream	Underflow	Bedrock	Net Total Recharge		
1945	5639	16	132	5787	110	5677
1946	3436	16	583	4035	2048	1987
1947	1094	16	0	1110	3985	-2875
1948	1273	16	0	1289	5923	-4634
1949	2347	16	1351	3714	7861	-4147
1950	852	16	0	868	9798	-8930
1951	3881	16	0	3897	11736	-7839
1952	4885	16	2973	7874	13674	-5800
1953	2692	16	629	3337	15818	-12480
1954	3049	16	802	3867	15964	-12098
1955	3000	16	908	3924	16111	-12187
1956	2480	16	0	2496	16257	-13762
1957	787	16	2088	2891	16404	-13513
1958	3766	16	1603	5385	16550	-11165
1959	2336	16	0	2352	16903	-14551
1960	2318	16	503	2837	16352	-13515
1961	2065	16	0	2081	15801	-13721
1962	1634	16	0	1650	15251	-13600
1963	1914	16	0	1930	14965	-13034
1964	1690	16	0	1706	11962	-10256
1965	2392	16	0	2408	8960	-6552
1966	2138	16	3749	5903	5958	-54
1967	1969	16	2014	3999	6259	-2260
1968	1394	16	0	1410	6715	-5304
1969	2394	16	4757	7167	3899	3267
1970	1766	16	0	1782	3975	-2194
1971	1350	16	0	1366	4052	-2685
1972	1345	16	0	1361	4128	-2766
1973	949	16	66	1031	4204	-3173
1974	1595	16	7973	9584	4280	5304
1975	617	16	0	633	4356	-3723
1976	833	16	880	1729	4432	-2703
1977	2391	16	0	2407	4508	-2101
1978	3989	16	11239	15244	4584	10660
1979	6682	16	2031	8729	5949	2780
1980	26061	16	19858	45935	6202	39732
1981	6128	16	0	6144	6455	-311
1982	6601	16	470	7087	6709	378
1983	21160	16	1226	22402	7875	14527
1984	6740	16	0	6756	8440	-1684
1985	4976	16	73	5065	8810	-3745
1986	4265	16	855	5136	9004	-3869
1987	3155	16	0	3171	9359	-6188
1988	2697	16	0	2713	10341	-7628
1989	2006	16	0	2022	10258	-8236
1990	1777	16	0	1793	10531	-8738
1991	3501	16	2571	6088	10807	-4719
1992	2999	16	3445	6460	11223	-4763
1993	16305	16	18733	35054	11948	23107
1994	1939	16	0	1955	12658	-10704
1995	7034	16	4590	11640	13548	-1908
1996	2267	16	0	2283	13817	-11534
1997	2283	16	2088	4387	13994	-9607
1998	7291	16	1603	8910	15012	-6102
1999	2235	16	0	2251	15106	-12855
2000	1966	16	503	2485	15296	-12811

Note: All recharge and groundwater production values are in units of acre-feet.

depleted approximately 510,000 acre-feet during the period from 1945 (steady-state) to 2000. The USGS had reported a net depletion from the aquifer, based on water level change, of 330,000 acre-feet between 1945 and 1980, indicating an additional depletion since then of 180,000 acre-feet (Moyle, 1982).

Figure 61 shows net difference between total net extractions and total recharge (referred to on this plot as “net water budget”). Also plotted for comparison in this figure, is total net extraction and water levels from two wells that are representative of water level conditions throughout the aquifer (10S/6E 21A1 and “Empty”). The symmetry of these curves is clearly seen. As extractions exceeded recharge, resulting in a negative net water budget through about 1966, water levels declined. During the period from about 1966 through about 1980, extractions were approximately balanced by recharge, and water levels stabilized and may have even recovered somewhat. From about 1980 on, extractions again exceeded recharge, resulting in a negative net water budget and water levels have responded by again declining. While water levels are almost a mirror image of groundwater extraction in the valley, large recharge events, indicated by the positive spikes on the net water budget curve have no real apparent effect on water levels. This may indicate that the influence of recharge on water levels is attenuated with distance from the sources of recharge, which are around the very perimeter of the valley, and even when there is significant recharge in any given year, its response to water levels is not immediately evident, dampened by the time it takes for groundwater to seep through the aquifer from the recharge areas to the vicinity of wells.

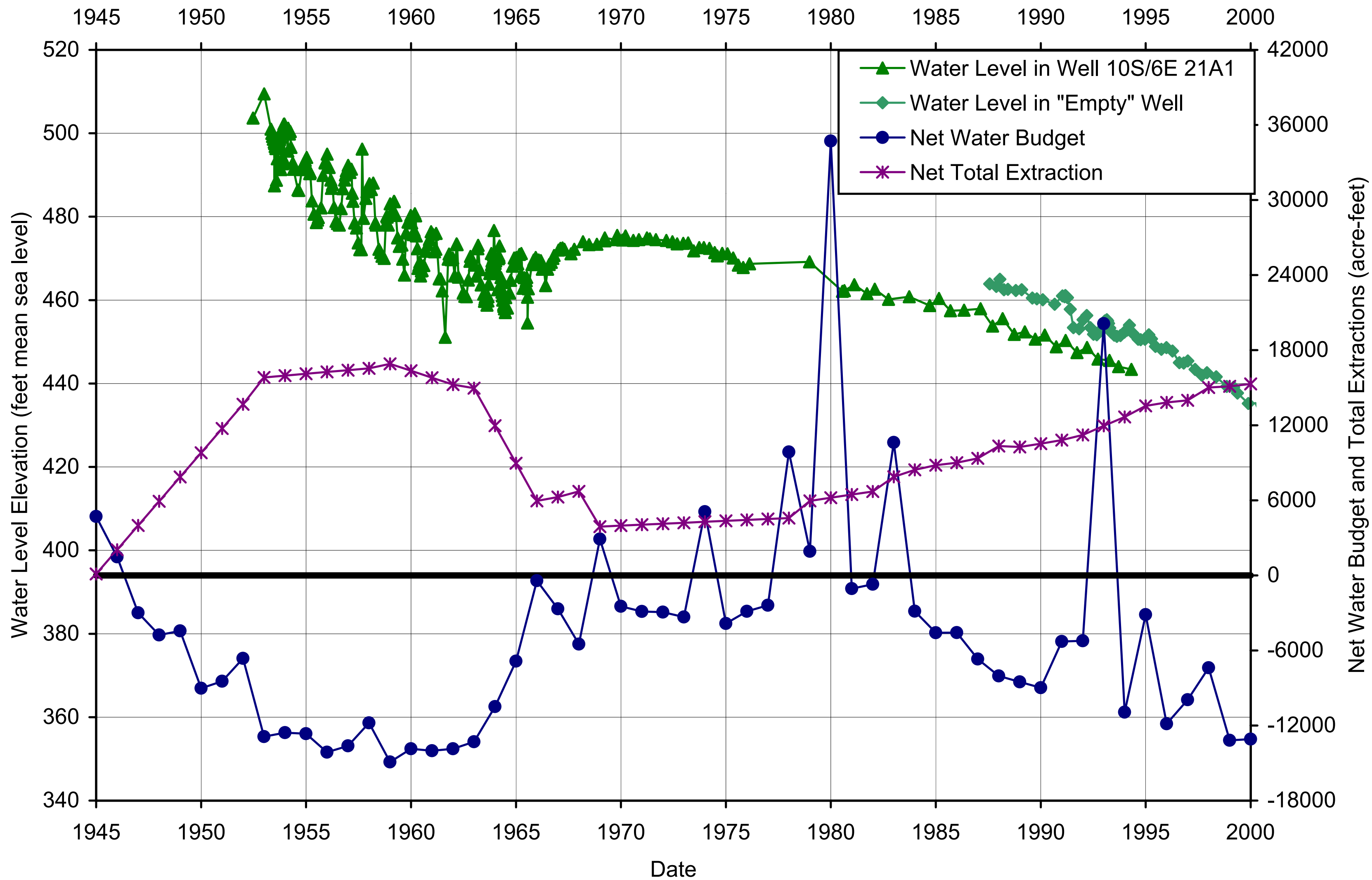


Figure 61. Net Water Budget-Water Level Comparison.

CHAPTER V

SUMMARY AND CONCLUSIONS

The primary purpose of this study was to define and evaluate the condition of the groundwater aquifer underlying Borrego Valley with sufficient detail to construct a numerical groundwater flow model. The specific objective was development of a conceptual model of the groundwater basin including (1) definition of the occurrence and distribution of geologic materials comprising the aquifer system, (2) characterization of the hydraulic properties of the aquifer materials, (3) evaluation of recharge to, and discharge from, the groundwater basin, and (4) quantification of the net loss of groundwater in storage from the Borrego Valley Aquifer. Development of the conceptual model was based primarily on: evaluation of lithologic logs, aquifer testing, water budget calculations, and analysis of water level trends. Previous studies related to groundwater in Borrego Valley were reviewed for pertinent information. However, the conceptual model derived from this study was made by independent analysis of all available data with the intent to provide more detail and a better understanding of the groundwater basin, resulting in a more useful model of the Borrego Valley aquifer system. The conceptual model of the groundwater basin is summarized as follows.

- The Cretaceous granitic and older metasedimentary rocks of northeastern San Diego County form the basement of the groundwater basin and crop out along the northern, western and southern margins of Borrego Valley as well as at Borrego Mountain. The basement complex rocks are exposed at or near the surface throughout much of the surrounding watershed.
- The geologic materials found within the groundwater basin include Tertiary rocks, predominantly the Palm Spring formation, and Quaternary alluvium. The Quaternary alluvium has been divided into older, intermediate and younger alluvium and is mostly comprised of alluvial fan and intermittent stream deposits, as well as some lacustrine deposits found within the intermediate alluvium.
- The aquifer system is comprised of four hydrogeologic units of Quaternary and Tertiary age. The uppermost three units are the Quaternary Alluvium, designated as younger, intermediate and older, each with varying hydraulic

properties. The oldest and lowermost unit is the Tertiary Palm Spring Formation. The hydrogeologic units are underlain by the Cretaceous and older crystalline basement rocks.

- The Quaternary older alluvium is the principal water-bearing unit of the aquifer. It is relatively coarse grained and is thickest in the northern portion of the basin.
- Hydraulic conductivity throughout the aquifer system is dependent on the distribution of soil texture within the hydrostratigraphic units. Within the alluvium, soil texture is generally coarse grained in the northern portion and along the margins of the basin, where it is closer to the source areas. Soil texture within the alluvium typically grades to finer grained towards the center of the valley at Borrego Sink.
- Aquifer test results indicate hydraulic conductivity of the older alluvium in the northern portion of Borrego Valley is on the order of 300 to 350 feet per day. Hydraulic conductivity in the distal portions of the older alluvium in central Borrego Valley was measured at 17 feet per day. Hydraulic conductivity of the relatively shallow portions of the Palm Spring formation in southern Borrego Valley was measured at 10 feet per day.
- Specific yield could not be measured during aquifer tests that were conducted in Borrego Valley, due to pumping duration constraints and lack of observation wells. No previous measurements of specific yield are known to have been made in Borrego Valley.
- Groundwater flow through Borrego Valley is primarily from the areas of recharge around the perimeter of the basin toward the topographic low at Borrego Sink, except where intercepted by cones of depression created by pumping wells in the valley. From the area around Borrego Sink, groundwater is consumed by phreatophytes or continues to flow east, probably across the Coyote Creek Fault, and along the approximate course of San Felipe Creek where it swings around the northern end of Borrego Mountain.
- Groundwater in the Borrego Valley appears to be isolated from Lower Borrego Valley. Isolation occurs in southern Borrego Valley due to the thick sequence of Palm Spring formation which is at or near the surface in the vicinity of Desert Lodge and the Sleepy Hollow folds; and may also be due to

the geometry of the basement complex, which is relatively shallow in the area from Yaqui Ridge to Borrego Mountain.

- Water levels have declined since major groundwater production began after 1945, except for a relatively brief period from the late 1960's to the late 1970's when there was a reduction in agricultural water use in the valley. During the last several years, water levels in the majority of monitored wells have been falling from approximately 1 foot per year to 3.5 feet per year.
- The primary source of recharge to the Borrego Valley aquifer is from infiltration of runoff from the several creeks and intermittent streams that drain to the valley from the mountains of the surrounding watershed. This *stream recharge* has been estimated to range from approximately 600 acre-feet to approximately 26,000 acre-feet annually, and average 3,860 acre-feet per year during the period 1945 through 2000.
- *Bedrock recharge* is another important source of recharge to the Borrego Valley aquifer, and is estimated to average nearly 1,800 acre-feet per year. Bedrock recharge occurs as subsurface seepage into the aquifer from the fractured crystalline basement rocks surrounding the basin.
- Total recharge, calculated as the sum of stream and bedrock recharge, is highly variable, ranging from approximately 600 acre-feet in 1975 to approximately 46,000 acre-feet in 1980, a range of almost two full orders of magnitude within a time period of only 5 years. Total recharge to the Borrego Valley aquifer has been estimated to average 5,670 acre-feet per year.
- Water applied for irrigation that is not consumed by plants or evaporated from the soil infiltrates through the vadose zone and returns to groundwater as irrigation return flow. Estimates of irrigation return flow were made by applying the chloride mass balance technique to soil samples collected from a citrus orchard and a golf course fairway. An estimated 22 percent of applied irrigation water in citrus orchards is returned to groundwater, while an estimated 14 percent of water applied to golf courses returns to groundwater. Other irrigation in the Valley is assumed to return at the 14 percent rate measured for golf courses.
- Net total groundwater extraction from the Borrego Valley aquifer was estimated based on well production records, where available, and depicted land use from aerial photographs. Net total groundwater extraction is

estimated to have ranged from approximately 100 acre-feet in 1945 to approximately 17,000 acre-feet in 1959. Net total groundwater extraction was estimated at 15,300 acre-feet in 2000.

- A net water budget was calculated as the difference between total recharge and net total groundwater extraction. Groundwater extraction has exceeded recharge in all but the wettest years since 1947, averaging a net loss of groundwater in storage due to overdraft of approximately 4,100 acre-feet per year during the period 1945 to 2000. For the year 2000, the net overdraft was estimated at approximately 12,800 acre-feet.
- Considering all sources of groundwater discharge, including evapotranspiration and groundwater underflow out of the basin, as fully reported by Henderson (2001), net total depletion of groundwater in storage within the Borrego Valley aquifer was estimated at 510,000 acre-feet as of the year 2000.

This new conceptualization of the geometry and hydraulic property distribution of hydrostratigraphic units, coupled with the water budget estimations, have been used to develop the overall conceptual model of the groundwater basin. This conceptual model, with some slight modifications, was used to construct a numerical groundwater flow model of the aquifer system (Henderson, 2001). The model was calibrated and used to simulate two projected groundwater use scenarios, expected growth and maximum probable growth. In both cases projected water levels continued to decline, as would be expected as long as groundwater production exceeds natural groundwater recharge to the aquifer system.

Continued overdraft of the aquifer will inevitably lead to continued decline in groundwater levels, resulting in increasing water costs as the water lift increases, and dry wells need to be replaced with successively deeper wells. In addition, continued drawdown of groundwater levels could increase the risk for upconing of deeper poor quality water that would be associated with the marine Imperial Formation, which is expected to occur at depth in Borrego Valley. Mitigation of the overdraft of groundwater in Borrego Valley could be accomplished by reducing groundwater production, so that is balanced by natural groundwater recharge. A cooperative groundwater management group with representation of all water users in the valley will need to decide how this could be accomplished. Otherwise legal intervention may become unavoidable and could lead to adjudication of water rights within the basin.

REFERENCES

Agbabian Associates, 1997. Personal communication and unpublished data.

Allison G.B., and M.W Hughes, 1983. The use of natural tracers as indicators of soil-water movement in a temperate semi-arid region. *Journal of Hydrology* 60, 157-173.

Allison, G.B., G.W. Gee, and S.W. Tyler, 1994. Vadose-zone techniques for estimating groundwater recharge in arid and semi arid regions. *Journal of the Soil Science Society of America* 58, 6-14.

Bauer, S., 1997. Personal communication.

Birsoy, Y.K., and W.K. Summers, 1980. Determination of aquifer parameters from step tests and intermittent pumping data. *Groundwater* 18, 137-146.

Borrego Water District, 2001. Groundwater Management Study, Report of the Technical Committee, February 2, 2001.

Brown, J.S., 1923. The Salton Sea region, California, A geographic guide to desert watering places. U.S. Geological Survey Water-Supply Paper 497.

Burnham, W.L., 1954. Data on water wells in Borrego, Ocotillo, San Felipe, and Vallecito Valley areas, eastern San Diego County, California. U.S. Geological Survey Open-File Report.

Burzell, L., 1997. Personal communication.

California Department of Public Works, Division of Water Resources, 1948. Evaporation from Water Surfaces in California, Basic Data. Bulletin No. 54-A.

_____, 1955. Evaporation from Water Surfaces in California. Bulletin No. 54-B.

California Department of Water Resources, 1975. Vegetative Water Use in California, 1974. Bulletin No. 113-3.

_____, 1981. A Preliminary Evaluation of Recharging the Borrego Valley Ground Water Basin with Local Runoff. Technical Information Record 1335-4301-A, by H. Iwanaga.

_____, 1983a. A Preliminary Evaluation of Cost of Imported Water Supplies to the Borrego Valley. Technical Information Record 1335-12-C-3, by K.K. Hatai.

_____, 1983b. A Preliminary Evaluation of Historical and Projected Water Demand for Borrego Valley. Technical Information Record 1335-12-C-1, by K.K. Hatai.

_____, 1983c. Preliminary Evaluation of Annual Recharge to the Borrego Valley Ground Water Basin. Technical Information Record 1335-11-B-1, by K.K. Hatai.

_____, 1984a. Evaluation of Future Operations of the Borrego Valley Ground Water Basin. Technical Information Record 1335-11-B-2, by P. Louie and H. Iwanaga.

_____, 1984b. Borrego Valley Water Management Plan.

California Division of Mines and Geology [CDMG], 1959. Geology and Mineral Resources of San Diego County, California. Map, in *Mines and Mineral Resources of San Diego County California*. County Report 3, 1963.

_____, 1977. *Geology and Mineral Resources of Imperial County, California.* County Report 7.

Cooper, H.H., and C.E. Jacob, 1946. A generalized graphical method for evaluating formation constants and summarizing well field history. *Transactions, American Geophysical Union* 27, 526-534.

Dibblee, Jr., T.W., 1954. Geology of the Imperial Valley Region, California. In *Geology of Southern California.* California Division of Mines, Bulletin 170.

_____, 1984. Stratigraphy and tectonics of the San Felipe Hills, Borrego Badlands, Superstition Hills, and vicinity. In *The Imperial Basin-Tectonics, Sediments, and Thermal Apects:* ed., Rigsby, C.A., 31-34. Pacific Section S.E.P.M.

Driscoll, F.G., 1986. *Groundwater and Wells*. 2^{nd} edition, Johnson Division, St. Paul, Minnesota, 1089 pp.

Durbin, T.J. and Berenbrock, C., 1985. Three-dimensional simulation of free-surface aquifers by finite-element method, in *Selected Papers in the Hydrologic Sciences 1985*. U.S. Geological Survey Water-Supply Paper 2270, 51-67.

Fetter, C.W., 1988. *Applied Hydrogeology.* 2^{nd} edition, Macmillan Publishing Company, New York, New York, 592 pp.

Fortiner, S., 1997. Personal communication.

Freeze, R.A., and Cherry, J.A., 1979. *Groundwater.* Prentice Hall, Inc., Englewood Cliffs, New Jersey.

Golden Software, Inc., 2000. Surfer Version 7.02 (surface mapping program).

Gorton, A., 1997. Personal communication.

Henderson, T.W., 2001. *Hydrogeology and Numerical Modeling of the Borrego Valley Aquifer System*. Masters Thesis, San Diego State University, Fall 2001.

Huntley, D., 1989. STEP (step-drawdown analysis program).

_____, 1990. RECHARG2 (soil water balance – groundwater recharge program).

Leeder, M.R., 1982. *Sedimentology: Process and Product.* Harper Collins Academic, London, UK.

Leeden, F.V.D., F.L.Troise, and D.K. Todd, 1990. *The Water Encycopedia*. 2nd edition, Lewis Publishers, Chelsea, Michigan.

Linsley, Jr., R.K., M.A. Kohler, and J.L.H. Paulhus, 1958. *Hydrology for Engineers.* McGraw-Hill, New York, New York.

Martin, C.M., 1995. *The Re-Interpretation of Gravity Data from Borrego Valley, California*. Senior Thesis, San Diego State University, Fall 1995.

McCloskey, T.F., and E.J. Finnemore, 1996. Estimating hydraulic conductivities in an alluvial basin from sediment facies models. *Groundwater* 34:6, 1024-1032.

Mendenhall, W.C., 1909. Some desert watering places in southeastern California and southwestern Nevada. U.S. Geological Survey Water-Supply Paper 224, 98 pp.

Merifield, P.M., and D.L. Lamar, 1986. Faults and Lineaments on Skylab Photographs of the Salton Trough Area, Southern California. In Guptil, P.D., E.M. Gath, and R.W. Ruff, eds., 1986. *Geology of the Imperial Valley, California.* South Coast Geological Society, Annual Field Trip Guidbook #14.

Mitten, H.T., G.C. Lines, C. Berenbrock, and T.J. Durbin, 1988. Water Resources of Borrego Valley and Vicinity, San Diego County, California: Phase 2--Development of a Ground-Water Flow Model. U.S. Geological Survey Water-Resources Investigations Report 87-4199, 27 pp.

Moyle, Jr., W.R., 1968. Water Wells and Springs in Borrego, Carrizo, and San Felipe Valley Areas, San Diego and Imperial Counties, California. California Department of Water Resources Bulletin 91-15.

_____ 1982. Water Resources of Borrego Valley and Vicinity, California, Phase 1--Definition of Geologic and Hydrologic Characteristics of Basin. U.S. Geological Survey Open-File Report 82-855, 39 pp.

National Oceanic and Atmospheric Administration [NOAA], 2001. Precipitation data, on-line download from NOAA, National Weather Information System (NWIS).

Peterson, J., 1997. Personal communication.

_____, 2001. Personal communication.

Prudic, D.E., 1994. Estimates of percolation rates and ages of water in unsaturated sediments at two Mojave Desert sites, California-Nevada. U.S. Geological Survey Water-Resources Investigations Report 94-4160, 18 pp.

San Diego County, Department of Planning and Land Use [DPLU]. Aerial photo series for the years: 1953, 1959, 1963, 1968, 1979, and 1992.

Scanlon, B.R., 1991. Evaluation of moisture flux from chloride data in desert soils. *Journal of Hydrology* 128, 137-156.

Searcy, J.K., and C.H. Hardison, 1960. Double-Mass Curves, Manual of Hydrology: Part 1. General Surface-Water Techniques. U.S. Geological Survey Water-Supply Paper 1541-B. *Methods and practices of the Geological Survey,* 66 pp.

Slade, 1997. Personal communication.

Sukhija, B.S., D.V. Reddy, P. Nagabhushanam, and R. Chand, 1987. Validity of the environmental chloride method for recharge evaluation of coastal aquifers, India. *Journal of Hydrology* 99, 349-366.

Theis, C.V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. *Transactions, American Geophysical Union* 16, 519-524.

Thornthwaite, C.W., and J.R. Mather, 1955. *The Water Balance*, Publication 8. Centerton, N.J.: Laboratory of Climatology, pp. 1-86.

_____, 1957. *Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance*, Publication 10. Centerton, N.J.: Laboratory of Climatology, pp. 185-311.

Threet, R.L., 1972. Hydrogeology of Southern Borrego Valley. Prepared April 13, 1972 for: George J. Kuhrts III, Borrego Springs, California.

_____, 1995. Personal communication.

U.S. Bureau of Reclamation, 1968. Inland basins projects, Borrego Valley, California. U.S. Bureau of Reclamation, interim report, 62 pp.

_____, 1972. Inland basins projects, California and Nevada. U.S. Bureau of Reclamation Reconnaissance Investigations, Chapter 7, 15-22.

U.S. Department of Agriculture [USDA], 1973. Soil Survey, San Diego Area, California.

Waring, G.A., 1915. Springs of California. U.S. Geological Survey-Water Supply Paper 338, 410 pp.

Zinser, R., 1996. Personal communication.

.

ABSTRACT OF THE THESIS

Water Resources of Borrego Valley
San Diego County, California
by
Steven Paul Netto
Master of Science in Geological Sciences
San Diego State University, Fall 2001

The groundwater aquifer system underlying Borrego Valley currently represents the sole source of water to the town of Borrego Springs and the surrounding community for municipal, agricultural and recreational demands. Groundwater has been extracted from the Borrego Valley aquifer since the early part of the 20th century. Beginning in the late 1940's and occurring throughout much of the period of groundwater development in Borrego Valley, groundwater extraction has exceeded natural groundwater recharge, resulting in an apparent overdraft condition. The net depletion of groundwater from storage within the aquifer system was approximately 510,000 acre-feet during the period 1945 through 2000. Overdraft of the aquifer has resulted in a decline of groundwater levels in the majority of monitored wells. Recent monitoring has indicated that water levels are currently declining an average of approximately 2 feet per year. Continued overdraft of the aquifer will inevitably lead to continued decline in groundwater levels, resulting in increasing water costs as water lifts increase and dry wells need to be replaced with successively deeper ones. In addition, continued drawdown of groundwater levels could increase the risk of upconing of deeper poor quality water.

The Borrego Valley aquifer system is comprised of four hydrogeologic units of Quaternary and Tertiary age. The uppermost three units are the Quaternary Alluvium, designated as younger, intermediate and older. The oldest and lowermost unit is the Tertiary Palm Spring formation. The hydrogeologic units are underlain by the Cretaceous and older crystalline basement rocks. The Quaternary older alluvium is the principal water-bearing unit of the aquifer. It is relatively coarse grained and is thickest in the northern portion of the basin. Within the alluvium, soil texture is generally coarse grained in the northern portion and along the margins of the basin, where it is closer to the source areas. Soil texture within the alluvium typically grades finer towards the center of the valley at Borrego Sink. Aquifer tests indicate hydraulic conductivity in the older alluvium in the northern portion of Borrego Valley on the order of 300 to 350 feet per day, in the distal portions of the older alluvium in central Borrego Valley at 17 feet per day, and in the relatively shallow portions of the Palm Spring formation in southern Borrego Valley at 10 feet per day. Groundwater in the Borrego Valley appears to be isolated from Lower Borrego Valley. Isolation occurs in southern Borrego Valley due to the thick sequence of Palm Spring formation, which is at or near the surface in the vicinity of Desert Lodge and the Sleepy Hollow folds; and may also be due to the geometry of the basement complex, which is relatively shallow in the area from Yaqui Ridge to Borrego Mountain.

The primary source of recharge to the Borrego Valley aquifer is from infiltration of runoff from the several creeks and intermittent streams that drain to the valley from the mountains of the surrounding watershed. This stream recharge has been estimated to have ranged from approximately 600 acre-feet to approximately 26,000 acre-feet annually, and average 3,860 acre-feet per year during the period 1945 through 2000. Bedrock recharge is another important source of recharge to the Borrego Valley aquifer, and is estimated to average nearly 1,800 acre-feet per year. Bedrock recharge occurs as subsurface seepage into the aquifer from the fractured crystalline basement rocks surrounding the basin. Total recharge, calculated as the sum of stream and bedrock recharge, is highly variable, ranging from approximately 600 acre-feet in 1975 to approximately 46,000 acre-feet in 1980, a range of almost two full orders of

magnitude within a time period of only 5 years. Total recharge to the Borrego Valley aquifer has been estimated to average 5,670 acre-feet per year.

Estimates of irrigation return flow were made by applying the chloride mass balance technique to soil samples collected from a citrus orchard and a golf course fairway. An estimated 22 percent of applied irrigation water in citrus orchards is returned to groundwater, while an estimated 14 percent of water applied to golf courses returns to groundwater. Other irrigation in the Valley is assumed to return at the 14 percent rate measured for golf courses. Net total groundwater extraction from the Borrego Valley aquifer was estimated based on well production records, where available, and depicted land use from aerial photographs. Net total groundwater extraction is estimated to have ranged from approximately 100 acre-feet in 1945 to approximately 17,000 acre-feet in 1959. Net total groundwater extraction was estimated at 15,300 acre-feet in 2000. A net water budget was calculated as the difference between total recharge and net total groundwater extraction. Groundwater extraction has exceeded recharge in all but the wettest years since 1947, averaging an overdraft of approximately 4,100 acre-feet per year during the period 1945 to 2000. For the year 2000, the net overdraft was estimated at approximately 12,500 acre-feet.

PLATE I HYDROGEOLOGIC CROSS-SECTIONS