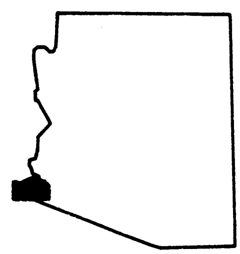
ARIZONA DEPARTMENT OF WATER RESOURCES
IN COOPERATION WITH
YUMA COUNTY FLOOD CONTROL DISTRICT

HYDROGEOLOGY, NUMERICAL MODEL AND SCENARIO SIMULATIONS OF THE YUMA AREA GROUNDWATER FLOW MODEL ARIZONA, CALIFORNIA, AND MEXICO



BY

BRADLEY M. HILL

HYDROLOGY DIVISION

MODELING REPORT NO. 7

ARIZONA DEPARTMENT OF WATER RESOURCES

Phoenix, Arizona

October, 1993

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HYDROGEOLOGY, NUMERICAL MODEL AND SCENARIO SIMULATIONS OF THE YUMA AREA GROUNDWATER FLOW MODEL ARIZONA, CALIFORNIA, AND MEXICO

FINAL REPORT

October 15, 1993

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BRADLEY M. HILL

Modeling Report No. 7

Groundwater Modeling Section
Hydrology Division
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EXECUTIVE SUMMARY

The Yuma area, which includes portions of the United States and Mexico, has experienced agricultural development since the late 1890s. Groundwater levels have risen throughout the Yuma area since the early 1900s due to recharge from irrigation water and leakage from unlined canals, creating shallow water levels which have water logged residential areas and prime agricultural land. Groundwater levels have risen over 70 feet beneath the Yuma Mesa since the early 1900s. The Colorado and Gila Rivers flooded the region during 1983 through 1986 which compounded the existing shallow groundwater level problem. Yuma County Flood Control District approached the Arizona Department of Water Resources (ADWR) in 1988 to assist in addressing the problems associated with rising groundwater levels.

The purpose of this investigation is to develop a regional 3-dimensional groundwater flow model that will be useful to Yuma County for many purposes including the evaluation of remedial water management alternatives to mitigate their shallow groundwater level problems in the northern portion of Yuma Valley near the Hacienda Estates subdivision. The objective is to effectively simulate the regional hydrologic regime and develop a single, comprehensive database of detailed hydrologic, geologic, and agricultural data for the entire Yuma area.

An Overview committee was created to guide and provide assistance throughout the project. This committee assisted in data development, project guidance, and identifying model scenario simulations to evaluate which water management decision would be most effective in lowering groundwater levels in northern Yuma Valley. The committee consisted of representatives from a wide variety of local agencies which included: Yuma County, U.S. Bureau of Reclamation, U.S. Geological Survey, U.S. Bureau of Indian Affairs, International Boundary and Water Commission - United States Section, Quechan and Cocopah Indian Tribes, several irrigation districts including Yuma Mesa I.D.D., Yuma County Water Users' Association, Bard I.D., Wellton-Mohawk I.D.D., Yuma I.D., North Gila Valley I.D., Unit B I.D., Imperial I.D.D., and several local natural resources conservation districts.

A detailed analysis of the hydrogeology and water resources was conducted for the Yuma area. Three lithologic water-bearing zones were identified as the wedge, lower coarse gravel and upper, fine-grained zones. Hydraulic characteristics of each of these water-bearing zones were quantified and several multiple-well aquifer pumping tests were conducted on the upper, fine-grained zone. Surface water data were collected including stream flow for all primary rivers, canals and drains, construction characteristics for canals and drains, and river bottom elevation profiles. Groundwater pumpage data was collected and summarized for both the United States and Mexico.

A regional model was constructed using the U.S. Geological Survey computer code MODFLOW and was used to simulate hydrologic conditions from April 1978 through March 1989. The active model domain encompasses 900 square miles including portions of Arizona, California, Sonora, and Mexicali Valley, Mexico. The model has approximately 30,000 model cells distributed among four layers, each layer simulating a distinct hydrogeologic unit. Model cells range in size from 40 acres to 640 acres. The model simulates the hydraulic interconnection between the Colorado and Gila Rivers, primary canals and drains and the groundwater system.

Model Layer One corresponds to the upper, fine-grained zone on the Yuma Mesa and beneath the All-American canal. Layer Two corresponds to the thin silt and clay layer that composes the river valley floor and Clay B beneath the Yuma Mesa. Model Layer Three corresponds to the upper, fine-grained zone throughout the entire Yuma area and Layer Four is a combination of the lower, coarse-gravel zone and the upper portion of the wedge zone.

The model was calibrated for steady-state and transient-state groundwater flow conditions. Summer 1978 (i.e., April through September) was assumed to be representative of steady-state conditions. The transient-state model was calibrated in two parts: pre-Colorado River flooding (October 1978 through March 1983) and Colorado River flooding and post-flooding (April 1983 through March 1989). Several criteria were used to determine the accuracy of the model calibration. These criteria included comparing measured water levels to final model-simulated water levels, comparing hydrographs from selected wells to model-simulated water levels, comparing model-generated volumetric water budgets to conceptual estimates, and comparing model-simulated surface water flow, canal seepage and drain discharge to conceptual estimates. Special attention was given to calibrating the model in the area adjacent to the Hacienda Estates subdivision.

A sensitivity analysis was conducted to determine how sensitive the model solution is to uncertainty in each input variable. The model is most sensitive to vertical hydraulic conductivity, and agricultural recharge.

Model scenario simulations were conducted for several purposes. First, an initial "base case" simulation was conducted using the final calibrated year (i.e., April 1988 through March 1989) as a baseline from which to measure change. Second, the severe spring 1993 flooding along the lower Gila River prompted local government officials to utilize the model to predict what the potential impacts this flooding might have on the groundwater system. Third, the model was utilized to determine which water management alternative would be most effective in reducing the shallow water levels within the northern portion of Yuma Valley near the Hacienda Estates subdivision.

Nine scenario simulations were conducted as part of this project. Scenario simulations started where the transient-state model ended in April, 1989 and were conducted through March, 1997 for a total of eight years. It is imperative to understand when evaluating the change in groundwater elevations for each scenario simulation that the relative change is what is important and not the absolute water level change. The relative change indicates the model's general response to a given scenario stress while the absolute water level change may not be correct due to data limitations, uncertainty and error within the model. However, absolute changes in groundwater elevations were provided to illustrate the relative impacts of each of the scenario simulations for comparative purposes.

The first scenario involved conducting an initial "base case" simulation to establish a baseline from which to measure change. This scenario was conducted by holding the model input data constant for the entire eight year simulation. The model input data were held constant to the final transient-state calibrated water year (i.e., April 1988 through March 1989).

The second scenario involved simulating the spring 1993 Gila River flooding to predict where the maximum groundwater level rises might exist due to the flooding. The third scenario simulated the identical flooding while pumping the existing drainage well network to determine if the well configuration would be effective in minimizing the impacts from groundwater level rises due to the recent flooding.

The results of the two flooding simulations indicated that the spring 1993 Gila River flooding should have a minimal impact on the groundwater system. Water levels were predicted to rise several feet adjacent to the Gila and Colorado rivers after 6 months. The maximum water level rises were predicted occur within one to two miles away from the rivers and should not adversely impact agricultural or residential areas. However, four years after the flooding ceased the model predicted no residual effects on the groundwater system and water levels declined to pre-flooding elevations. The existing drainage well network significantly reduced any water level rises due to the flooding, especially in the northern Yuma Valley where the majority of the wells are located.

The next five scenario simulations addressed potential water management alternatives to lowering the shallow groundwater levels in the northern portion of Yuma Valley near the Hacienda Estates subdivision. These simulations included: lining four miles of the East Main canal adjacent to the Hacienda Estates subdivision, lining of the East Main canal and pumping drainage wells DW 14 and DW 15 located near the Hacienda Estates subdivision, reducing deep percolation recharge from excess agricultural irrigation within the Yuma Valley and on Yuma Mesa, and lining the entire length of the All-American canal within the Yuma area.

The results of lining four miles of the East Main canal adjacent to the Hacienda Estates subdivision indicate that water levels were predicted to decline a maximum of approximately one foot after four years along a relatively narrow zone near the canal. However, lining the canal and pumping drainage wells DW 14 and DW 15 had the greatest impact on lowering groundwater levels of all the scenarios. This scenario predicted that water levels would decline a maximum of six feet after four years near the subdivision.

Reducing deep percolation recharge from agricultural irrigation by 25 percent also had a significant impact on lowering water levels near the Hacienda Estates subdivision. The model predicted that reducing recharge by 25 percent on Yuma Mesa would lower water levels adjacent to the subdivision over two feet while lowering water levels on the groundwater mound over nine feet after four years. Reducing recharge by 25 percent in Yuma Valley was predicted to lower water levels by approximately one foot near the subdivision after four years. These scenarios illustrate the potential influence excess agricultural irrigation has on groundwater levels within the Yuma area. However, the model could not accurately simulate the maximum effects deep percolation recharge has on groundwater levels since the areal location of where crops were grown and water was applied could not be identified sufficiently.

Lining the entire All-American canal within the Yuma area had a significant impact on lowering water levels on the north side of the Colorado River near the Quechan Indian Reservation in California. Groundwater levels were predicted to decline up to nine feet beneath the canal and range between one and five feet within the reservation area after four years. This simulation also predicted that water levels would decline near the Hacienda Estates subdivision a maximum of one foot after four years. The impacts from lining the canal on groundwater levels south of the Colorado River near the subdivision can be attributed to the fact that the river only partially penetrates the aquifer in the Yuma area.

The final model scenario simulation was conducted to evaluate the hydrologic importance of the clayey-zone beneath the Yuma Mesa. This clayey-zone, informally identified as Clay B, is thought to play an important role hydrologically by inhibiting the vertical movement of groundwater flow beneath the Yuma Mesa. This simulation removed all hydraulic characteristics of this layer and replaced them with those of the upper, fine-grained zone. The results of this simulation indicated that in conjunction with recharge from excess agricultural irrigation, Clay B has a great impact on creating the groundwater mound beneath the Yuma Mesa. Groundwater levels declined over 16 feet after four years assuming the recharge rates for 1988/89 were held constant.

Conclusions of this project indicate that the shallow water levels near the Hacienda Estates subdivision are the result of several factors including: the area has been historically an area of shallow groundwater levels, effects of the groundwater mound beneath the Yuma Mesa, changes in crop types in the Yuma Valley to vegetable crops, seepage from the East Main canal, and to a much lesser degree the short-term transient effects from the historical flooding of the Colorado River.

ACKNOWLEDGEMENTS

I would like to recognize Frank G. Putman and Dale A. Mason within the ADWR Hydrology Division for their contribution towards this project. Frank Putman for his guidance and general oversight and Dale Mason for his direct technical assistance. I could not have completed this project without the extensive contribution by Dale Mason regarding database management, model simulation runs, field collection of aquifer test data and final report preparations.

Yuma County Flood Control District must be recognized for their initial funding and primary impetus for getting this project off the ground. Roger Schoenherr played an instrumental role in the coordination and management of this project through the Overview Committee. Thanks should be extended to each member of the Overview Committee for their guidance, and support with special recognition to the irrigation districts who provided necessary data and other assistance to this project. The Overview Committee should also be recognized for developing the list of model scenario simulations conducted as part of this modeling effort.

The U.S. Bureau of Reclamation - Yuma Projects Office must be recognized for their technical assistance and data development. The U.S. Bureau of Reclamation provided the majority of the raw hydrologic, geologic and agricultural related data used for this project. Special thanks is extended to Earl Burnett and Fred Croxen for their contribution in providing and collecting data and their assistance in understanding the hydrologic complexities of the Yuma area.

Two individuals from the U.S. Geological Survey deserve recognition for their contribution towards this project; Stan A. Leake for his technical guidance and oversight and David E. Prudic for his assistance in designing and applying the streamflow-routing package to the complex surface water system within the Yuma area.

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CHAPTER I. INTRODUCTION

Problem

The Yuma area (Figure 1) has experienced irrigated agricultural development since the 1890s. Expansion of irrigated acreage occurred in 1904 when the U.S. Bureau of Reclamation (USBR) began constructing the Yuma Project which carried Colorado River water to the Yuma Valley (Figure 2). Irrigation on Yuma Mesa first began in 1923 with the construction of the Unit B - Yuma Auxiliary Project (Iakisch and Sweet, 1948). Because of the increased irrigation and unlined conveyance canals, groundwater levels began to rise within the valley areas. To address the rising groundwater levels an extensive drainage canal network was constructed within Yuma Valley beginning in 1916 (Iakisch and Sweet, 1948). This drainage canal network in combination with the pumping of numerous drainage wells effectively managed the shallow groundwater levels for the following 70 years.

The Colorado and Gila Rivers flooded the region between 1983 and 1986. During the flooding, the stage of the Colorado River increased 17 feet at the Yuma Gage near the Fourth Avenue Bridge (Mock and others, 1988). This increased stage height prevented the river from being a natural groundwater drain, and instead became a source of recharge to the Yuma area. Groundwater levels adjacent to the river increased 8 to 13 feet compounding the problem of shallow groundwater levels (Mock and others, 1988).

The groundwater levels away from the river remained shallow even after the river flows subsided after 1984. These shallow groundwater levels are currently impacting residential areas and prime agricultural land. However, the cause of the shallow water levels is uncertain, and has been attributed to either the river flooding or change in crop types to more vegetables in the Yuma Valley during the same period.

Shallow groundwater levels have created severe problems within the valley areas. These problems include reduced efficiency of septic tanks, stability problems for structures built in these areas, inability to flush soils of salt build-up, and difficulty in harvesting crops when fields are too saturated for the heavy machinery to operate properly (Mock and others, 1988).

In 1988, Yuma County Flood Control District approached the Arizona Department of Water Resources for assistance in evaluating solutions to the shallow groundwater level problems. An intergovernmental contract was signed in October 1990 to study the region and construct a three-dimensional groundwater/surface water flow model to be used to evaluate remedial water management scenarios to address their shallow groundwater level problems.

Purpose and Objectives

The purpose of this investigation is to develop a regional three-dimensional groundwater flow model of the Yuma area that will be useful for Yuma County and other local interests in understanding and evaluating solutions to their water management problems. The general objectives are to develop a numerical model that effectively simulates the groundwater/surface water regime, accumulate all hydrologic, geologic, agricultural data for the entire Yuma area into a single database format and provide analysis of specific predictive scenario model simulations that will assist in evaluating solutions to the current water management problems in the Yuma area.

Description of the Area

The Yuma area is located geographically at the downstream end of the Colorado River basin and is comprised of portions of the United States and the Republic of Mexico (Figure 1). California borders Yuma on the north and the Mexican states of Baja California and Sonora border Yuma on the west and south, respectively. This geographic setting makes the Yuma area unique from a political and water resource perspective. Any water resource related decision implemented within Arizona must take into account the potential impacts within both California and Mexico.

Management of the Colorado River is controlled by several federal legislative acts, state compacts and an international treaty (Nathanson, 1978). The Colorado River Compact of 1922, among other things, divided the Colorado River into two basins at Lees Ferry which is located in northern Arizona downstream of Glen Canyon Dam. This compact established that both the

Upper and Lower Basins are entitled to 7.5 million acre-feet of Colorado River water. The Yuma area which is located within the Lower Basin is also subject to the Mexican Water Treaty of 1944 and the Salinity Control Act of 1973. The Treaty provided Mexico with an entitlement of 1.5 million acre-feet of Colorado River water annually but did not address water quality. The Salinity Control Act of 1973 addressed the high salinity levels of the Colorado River being delivered to Mexico. The Act, among other things, required the Colorado River diverted into Mexico to be of similar water quality to that entering the Yuma area at Imperial Dam. One method to achieve this was to construct a Desalting Plant to treat Wellton-Mohawk drainage water (Nathanson, 1978).

Most of the Yuma area is within the Sonoran Desert section of the Basin and Range physiographic province, except for the southwestern part which is part of the Salton Trough section of the province. The area is situated at the apex of the Colorado River delta approximately 70 air miles north of the Gulf of California (Olmsted and others, 1973). The region is bounded on the north by the Cargo Muchacho, Chocolate and Laguna Mountains, and on the east by the Gila and Tinajas Atlas Mountains. The region is adjacent to the Altar Desert of Sonora, Mexico to the south and Mexicali Valley of Baja California, Mexico to the west.

The Yuma area is one of the driest areas in North America with an annual precipitation of approximately three inches. In July, the mean daily maximum temperature is 107° F and the mean daily minimum is 80° F. In January, the mean daily maximum temperature is 69° F and the mean daily minimum is 43° F (National Weather Service, 1993).

This portion of the Sonoran desert is characterized by sparse vegetation with creosote bush and mesquite the predominate vegetation type in the desert lowlands. The areas immediately adjacent to the Colorado and Gila Rivers are covered with riparian plant communities. Salt cedar, cottonwood and willow are the predominate vegetation types within floodplains of the Yuma area (Younker and Anderson, 1986).

The Yuma region is divided into six subareas based upon natural geographic boundaries and hydrogeology. The subareas include Yuma Valley, Reservation, North Gila, South Gila, Yuma Mesa and Laguna Valley (U.S. Bureau of Reclamation, 1978-1989a). However, the Laguna Valley is outside of the area of interest and is not part of this report. The Reservation subarea has been subdivided into the Bard and Reservation districts based upon separate irrigation distribution networks (Figure 3). The Wellton-Mohawk Valley along the Gila River east of the Gila Mountains is also considered to be part of the Yuma area but is hydrologically separated from these subareas and is not included in this report.

Previous Investigations

The U.S. Bureau of Reclamation (USBR) has historically collected large amounts of hydrologic data throughout the Yuma region since the beginning of this century. They have made numerous hydrologic studies to evaluate water management practices along the entire lower Colorado River region. The USBR has published an annual Ground-Water Status Report of the Yuma area since 1967 (U.S. Bureau of Reclamation, 1978-1989a). These reports contain water use information per subarea, annual groundwater pumpage per well owner and maps illustrating groundwater level elevation, depth to groundwater, and areal extent of irrigated agricultural development among others.

The most comprehensive geologic and hydrogeologic study of the Yuma area was conducted by Olmsted and others in 1973. This report contains a detailed analysis of geologic and hydrogeologic data throughout the Yuma area. The hydrogeologic framework for the construction of the numerical model was adopted entirely from this report. As a part of this same U.S. Geological Survey study, Patten (1977) developed a regional electric analog model of the Yuma area.

Several numerical models have been constructed of the Yuma area for different purposes. Loeltz and Leake (1983) studied methods of estimating return flows to the Colorado River between Laguna and Morelos Dams. They developed a series of two-dimensional cross-sectional models that were used to estimate the amount of groundwater discharging to the Colorado River. As a response to the flooding in 1983, the Arizona Department of Water Resources in cooperation with the U.S. Bureau of Reclamation developed two separate two-dimensional models to analyze the effects of the river at high stage and groundwater pumpage (Mock and others, 1988). Although these separate models were useful in evaluating the most effective method for lowering groundwater levels at that time, they were limited in their ability to evaluate the complex inter-relationship between all aspects of the groundwater and surface water system.

CHAPTER II. PHYSICAL SYSTEM

Overview of Geologic and Hydrologic System

The Yuma area located within the Sonoran desert is characterized by elongated, low, rugged mountains separated by extensive broad desert plains. The majority of the mountain ranges within the Basin and Range physiographic province trend approximately north-northwest (Olmsted and others, 1973). The Colorado River flows across the region through a series of narrow valleys and broad alluvial desert plains. The Gila River, which is the principal southern tributary to the Colorado River, flows west-southwest across the mountains and broad desert plains to join the Colorado River just east of the city of Yuma.

The Colorado River drainage basin covers 188,600 square miles of the country's hottest and driest lands (Boner and others, 1991). The river is 1,440 miles long and drains portions of seven western states including Wyoming, Colorado, Utah, New Mexico, Arizona, Nevada and California. The Colorado River is diverted into two major canals at Imperial Dam just upstream of Laguna Dam within the Yuma area. The All-American canal which flows on the north side of the Yuma area diverts water to the Imperial Valley in California and the Bard, Reservation and Yuma Valley areas in Arizona (Figure 3). The Gila Gravity Main canal which flows along the east side of the Yuma area diverts water to several areas within Arizona including the North Gila Valley, Wellton-Mohawk, South Gila Valley and Yuma Mesa. The Colorado River downstream of Yuma is now diverted entirely into Mexico at Morelos Dam as part of the International Treaty of 1944 (Figure 3). The normally dry Colorado River below Morelos Dam now only flows during high flood stages or in relation to prolonged flood control releases.

The Gila River drainage basin covers 57,850 square miles of central Arizona and western New Mexico (Boner and others, 1991). The Gila River enters the Yuma area from the east between the Laguna and Gila Mountains and flows into the Colorado River several miles east of the city of Yuma (Figure 3). The Gila River is perennial within the Yuma area according to gaging data east of Yuma near Dome Narrows.

The Colorado and Gila Rivers act as natural drains between Laguna and Morelos Dams during normal flow conditions. During normal flows, the river stage elevation is below the groundwater elevation in the adjacent aquifer indicating groundwater discharges into the river. However, during flood flows the river stage elevation is above the ground water elevation and the natural direction of groundwater flow is reversed and the river becomes a source of recharge. Topographically the Yuma area is characterized by low-lying floodplains, and ancient river terraces of the Colorado and Gila rivers and mesas surrounded by crystalline mountains on the north and east (Figure 3). The river floodplains are broad, flat areas that extend from the Chocolate and Laguna Mountains in the north to Mexicali Valley, Mexico to the southwest. These Holocene river deposits overlie a vast sequence of nonmarine and marine sedimentary deposits associated with the Colorado River delta (Olmsted and others, 1973). The axis of the delta trends west-southwest from Pilot Knob towards the Gulf of California. The floodplains are generally no longer subject to flooding since numerous upstream dams regulate the flows of the Colorado and Gila Rivers.

Terraces and mesas rise abruptly above the river floodplain and slope gently upward towards adjacent mountains. They represent a combination of dissected ancient river deposits or pediment slopes from the erosion of local mountains (Olmsted and others, 1973). The most prominent terrace and mesa feature in the Yuma area is called Yuma Mesa (Figure 3). The mesa escarpment rises approximately 50 feet abruptly above the floodplain, then gently slopes to the east towards the Gila Mountains.

The surrounding mountains are comprised of pre-Tertiary age crystalline igneous and metamorphic rocks and Tertiary age volcanic and nonmarine sedimentary rocks (Olmsted and others, 1973). The Cargo Muchacho, Gila, Tinajas Atlas Mountains and Pilot Knob are composed of granite, gneiss and schist. The Chocolate Mountains are comprised of volcanic rocks ranging in composition from rhyolite to basalt. The Laguna Mountains are composed primarily of nonmarine sedimentary rocks interlaced with outcrops of volcanic rocks (Olmsted and others, 1973).

The regional structural pattern of the Yuma area is due in part to block faulting associated with the Basin and Range physiographic province. However, most of the faults are buried by the broad alluvial pediments and must be inferred (Olmsted and others, 1973). The Algodones fault trends northwest from the Boundary Hills on the Mexican border towards Pilot Knob in the Yuma area (Figure 3). This fault is important for several reasons. First, the fault has created a ridge where the basement crystalline bedrock is relatively shallow beneath the Yuma Mesa. There are areas on the Yuma Mesa where depth to bedrock is less than 100 feet (Olmsted and others, 1973). The "Yuma hills" located at the northern end of Yuma Mesa are evidence where the bedrock outcrops above land surface. Besides creating a ridge of shallow bedrock, the fault is also importantly hydrologically. The fault creates a partial barrier to groundwater flow indicated by an offset in groundwater elevations on Yuma Mesa. Water levels are approximately 40 feet higher on the northeast side of the fault than on the southwest. The hydrologic influence of the fault diminishes to the north as the fault trace approaches the Yuma Valley.

The Fortuna Basin trends northwest and is situated between the Algodones fault and the Gila Mountains (Figure 3). This basin is filled with an estimated 10,000 feet of nonmarine and marine sedimentary rocks and may be important hydrologically, due to its ability to store vast amounts of groundwater (Olmsted and others, 1973).

Geologic cross-sections illustrate the relationship of the basement bedrock, overlying sedimentary rocks and influence of the Algodones fault on the water table. Figure 4 is a cross-section that trends west to east.

Water Bearing Units and General Hydraulic Characteristics

As previously mentioned, the Yuma area is underlain by thick sequences of nonmarine and marine sedimentary rocks. However, only the upper several hundred feet of these sediments are hydrologically important. This is because the upper layers are extremely transmissive and yield sufficient quantities of water to wells. Therefore, only the three upper most water bearing lithologic units are discussed in this section. From lowest to uppermost, these are the wedge zone, coarse-gravel zone, and the upper fine-grained zone. Figure 4 is a generalized geologic cross-section that illustrates the water bearing lithologic units relative to one another.

Wedge Zone

The wedge zone constitutes the major part of the water bearing deposits beneath the river valleys and Yuma Mesa (Olmsted and others, 1973). Throughout most of the region, this zone overlies the marine Bouse Formation and underlies the coarse-gravel zone. The thickness of the wedge zone is approximately 2500 feet near San Luis, Arizona and generally pinches out laterally beneath the coarse-gravel zone against adjacent crystalline mountains and the buried bedrock ridge under Yuma Mesa (Olmsted and others, 1973).

These older alluvial sediments consist of basin-filling fluvial and deltaic sediments deposited by the Colorado and Gila Rivers (Olmsted and others, 1973). The lithologic break between the wedge zone and the overlying coarse-gravel zone is sometimes vague and the two zones are undifferentiated in many locations. According to geologic logs, this zone consists of interbedded sands and gravels. The sand ranges in grain size from fine to coarse, and gravel and cobbles up to 2-3 inches in diameter are common (Olmsted and others, 1973).

Olmsted and others (1973) combined the upper portion of the wedge zone with the overlying coarse-gravel zone for hydrologic purposes, since data obtained from aquifer pumping tests include wells that are screened in both alluvial layers. Coefficients of transmissivity and storage were estimated from these aquifer pumping tests. Table 1 summarizes the hydraulic characteristics for each of the water bearing units in the Yuma area. The following description of the coarse-gravel zone contains a detailed discussion of the hydrologic characteristics of the upper portion of the wedge and coarse-gravel zones. Little to no hydrologic data exists for the lower part of the wedge zone.

Coarse-Gravel Zone

The coarse-gravel zone is the most permeable of the alluvial sediments in the Yuma area, and is penetrated by almost all water production wells. This zone is the principal aquifer beneath the river valleys and Yuma Mesa (Olmsted and others, 1973) (Figure 4). Throughout the region this zone overlies or is an undifferentiated part of the wedge zone and underlies the less permeable upper, fine-grained zone. Figure 5 illustrates the elevation above mean sea level of the top of the coarse-gravel zone.

Table 1
Hydraulic Characteristics of the Water Bearing Units Within the Yuma Area

Aquifer Parameters	*Upper Wedge and Coarse-Gravel Zones Combined*	*Upper, Fine-Grained Zone*
Transmissivity (1)	9000 - 240,000 Ft^2/Day	1,600-10,000 Ft^2/Day
Hydraulic Conductivity (2) (Horizontal)	Average <1,300 Ft/Day Maximum	50-500 Ft/Day
Hydraulic Conductivity (3) (Vertical)	≈ 0.10 Ft/Day	Undetermined
Storage Coefficient (4)	10^{-3}	10^{-3}
Specific Yield (5)	0.18 → 0.35	0.18 → 0.35

Notes:

(1) Upper wedge and coarse-gravel zones estimated from Olmsted and others (1973 p. 79). Upper, fine-grained zone estimated from multiple well aquifer pumping tests (ADWR, 1992).

(2) Coarse-gravel zone estimated from Olmsted and others (1973, p. 78). Fine-grained zone estimated from ADWR (1992). Hydraulic conductivity estimated by dividing transmissivity by saturated thickness. Saturated thickness estimated as the total depth of the observation well below static water level.

(3) Horizontal to vertical ratio of 10,000:1 (Harshbarger, 1971).

(4) Estimated from Harshbarger (1971), Jacob (1960).

(5) Estimated from Olmsted and others (1973).

These alluvial deposits consist of basin-filling fluvial and deltaic sediments from the Colorado and Gila Rivers and range in thickness from 0 feet to 100 feet within the Yuma area. Depth to the coarse-gravel zone ranges from approximately 100 feet in the river valleys to approximately 180 feet beneath the Yuma Mesa. According to geologic logs, this zone is comprised primarily of fine to coarse gravel with cobbles ranging in diameter up to 10 inches (Olmsted and others, 1973).

As previously mentioned, Olmsted and others (1973) hydrologically combined the coarse-gravel zone with the upper portion of the wedge zone, since hydrologic data obtained from aquifer pumping tests include wells that are screened in both alluvial layers. A map of aquifer transmissivity for the alluvium was constructed by Olmsted and others (1973, p. 81). In general, transmissivity increases towards the southwest and the Fortuna Basin and decreases towards the crystalline mountains and buried bedrock ridge beneath the Yuma Mesa (Figure 6).

The combined average horizontal hydraulic conductivity of these two zones is probably no greater than 1300 Ft/Day or 10,000 Gal/Day/Ft^2 (Olmsted and others, 1973, p. 78). The ratio of horizontal to vertical hydraulic conductivity beneath the western part of the Yuma Mesa was estimated at 10,000:1 (Harshbarger, 1971). Table 1 summarizes the hydraulic characteristics of each water bearing unit within the Yuma area.

Storage coefficients for the upper portion of the wedge and coarse-gravel zones were estimated from aquifer pumping tests and neutron moisture probe data from the Yuma Mesa. The magnitude of the storage coefficients indicate that the two zones are unconfined to semi-confined. Olmsted and others (1973) state that the change of groundwater in storage in the Yuma area is primarily due to gravity drainage or water level rise under water table conditions and not due to a confined pressure response. Most aquifer pumping tests conducted within the Yuma area probably under estimate the storage coefficient unless the tests are conducted for a sufficient amount of time to adjust for the delayed yield effect. Semi-confined storage coefficients were estimated from two long-term aquifer pumping tests. Jacob (1960) estimated the average storage coefficient at 1.2×10^{-3} along the eastern portion of Yuma Valley and Harshbarger (1971) estimated the average storage coefficient at 3.0×10^{-3} along the western edge of Yuma Mesa (Table 1). However, these semi-confined conditions are not assumed representative of the coarse-gravel zone throughout the entire Yuma area (Olmsted and others, 1973).

Olmsted and others (1973) assumed that storage coefficients obtained from neutron moisture probes on the Yuma Mesa are more representative. The tests were conducted to determine the moisture content above and below the water table and calculating the specific yield of the material. These values ranged between 0.18 and 0.35 and were used as initial estimates for storage coefficient for an electric analog model developed by the U.S. Geological Survey (Olmsted and others, 1973, p. 109).

Upper, Fine-Grained Zone

The upper, fine-grained zone is important hydrologically because much of the groundwater moves vertically through the layer and most of the shallow groundwater monitor wells are screened in the zone. The zone ranges in thickness from about 70 to 240 feet and averages about 100 feet beneath the river valleys and 170-180 feet beneath the Yuma Mesa (Olmsted and others, 1973). The upper fine-grained zone is comprised predominately of fine to medium sand and silt, however sandy gravels and clay layers can be locally extensive (Olmsted and others, 1973).

The upper, fine-grained zone overlies the coarse-gravel zone throughout the region. Beneath the river valleys it underlies a relatively thin layer of silt and clay which comprises the valley land surface (Figure 4). This layer of silt and clay has an approximate thickness of 5-15 feet and is important hydrologically since agricultural crops are grown on this layer and irrigation water is applied to the layer.

For the purposes of this report, the upper fine-grained zone is differentiated into 3 separate layers based upon lithology beneath the Yuma Mesa. Separating the upper fine-grained zone is a clay layer that has been informally named Clay B by Olmsted and others (1973). This is best illustrated by examining the geologic cross-section in Figure 4. Clay B is aerially extensive (42 square miles) and laterally continuous with the silt and clay layer that comprises the river valley land surface (Figure 7). This layer ranges in thickness between 10-15 feet and is comprised primarily of clay and silty clay with minor amounts of fine-sand and scattered pebbles. Clay B grades laterally into more gravelly deposits towards the southwest (Olmsted and others, 1973). Clay B is thought to play an important role hydrologically by inhibiting the vertical movement of groundwater flow beneath the Yuma Mesa. Figures 8 and 9 illustrate the elevation above mean sea level of the top and bottom of Clay B and the silt and clay layer in the river valleys. Figure 10 presents an isopach thickness map of this layer.

Olmsted and others (1973) have identified another regionally extensive clay layer named informally as Clay A. Clay A is not as laterally extensive (33 square miles) as Clay B and is located within the western portion of Yuma Valley. Clay A is stratigraphically located immediately above the coarse-gravel zone and below Clay B. This clayey zone ranges in thickness from several inches to over 35 feet in the southern part of Yuma Valley and is comprised primarily of silty-clay which grades laterally into more gravelly deposits (Olmsted and others, 1973). The areal extent of both clay zones were defined by geologic logs from test holes drilled throughout the area.

An isopach map illustrates the thickness of the fine-grained zone beneath the Clay B and silt and clay layer of the river valleys (Figure 11). This portion of the fine-grained zone thickens towards the southwest. Another isopach map illustrates the thickness of the sediments above Clay B beneath the Yuma Mesa (Figure 12). Both of these maps were created from data within the Yuma Mesa and Yuma Valley areas only. There were no data for Fortuna Basin or Mexico, therefore the layer thickness estimated for these areas were inferred for modeling purposes.

Estimates of transmissivity and storage coefficient for this zone were obtained via different methods. Transmissivity was estimated from several multiple-well aquifer pumping tests conducted as part of this modeling study by the U.S. Bureau of Reclamation and the Arizona Department of Water Resources (ADWR, 1992). Storage coefficients were estimated from neutron moisture probe data from the Yuma Mesa (Olmsted and others, 1973).

Figure 13 shows the locations of the well sites where the aquifer pumping tests were conducted. At each location, three 2.5 inch diameter wells were installed to a depth of 45 feet below land surface at a relative spacing of 5 feet between each well. One of the wells was then pumped at a constant rate while the other two were monitored for water level declines and recovery. Due to the small well casing diameter, maximum pumping rates were relatively low (e.g., 16-65 gpm). The ability to extensively stress the aquifer was minimized and water level declines stabilized within an hour. The short duration of these tests prohibited a valid estimation of a storage coefficient while transmissivity estimates are representative of a relatively small area. However, these tests provided important hydraulic data never before collected for the upper, fine-grained zone.

Transmissivity estimates obtained from these tests range from 1,600 to 10,000 Ft^2/Day and horizontal hydraulic conductivity from 50 to 500 Ft/Day (ADWR, 1992) (Table 2). In general, transmissivity estimates were greater towards the southern portion of Yuma Valley and lower towards the northern and eastern portions. The ratio of horizontal to vertical hydraulic conductivity was estimated, however the ratios were unrealistically too low and were concluded

Table 2
Transmissivity and Hydraulic Conductivity Summary of the Upper Fine-Grained Zone From Aquifer Pumping Tests Conducted by the USBR/ADWR

Site Location	*Transmissivity* Ft^2/Day		*Hydraulic Conductivity* Ft/Day	
	Low	**High**	**Low**	**High**
1. USBR-YPO Office Desalting Plant	5,000	7,600	170	250
2. Hacienda Estates	6,400	10,000	320	500
3. 13.5 Street near East Main Canal	1,600	3,600	50	100
4. Yuma Mesa I.D. Maintenance Yard	4,300	6,300	140	210
5. 18th Street/H½ Street	6,400	10,700	180	300
6. 13th Street near YCWUA Co. 13th Street Well	4,500	6,300	110	160

Notes:

(1) Results from observation wells during constant-discharge aquifer pumping tests.

(2) Data analyzed using a variety of analytical techniques (AQTESOLV Software) (Duffield and Rumbaugh, 1991).

(3) Hydraulic conductivity estimated by dividing transmissivity by aquifer thickness. Aquifer thickness estimated as the depth of the observation well below static water level.

(4) Storage coefficients were not estimated due to the short duration of tests.

(5) Refer to Appendix II for detailed explanation.

(6) Refer to Figure 13 for site locations.

not to be valid (i.e., too high of a vertical hydraulic conductivity). These low ratios are attributed to the data not meeting all the necessary physical and mathematical assumptions required of the analytical method used. Appendix II contains a complete explanation of the aquifer tests conducted, analytical methods used to evaluate the data and graphical plots.

Storage coefficients for the upper, fine-grained zone were estimated from neutron moisture probe data from the Yuma Mesa (Olmsted and others, 1973). As previously stated, groundwater storage changes in the Yuma area are primarily due to gravity drainage or water level rise under water table conditions and not due to confined pressure responses (Olmsted and others, 1973). Therefore, this layer is assumed to be under unconfined aquifer conditions. This assumption is appropriate since there is only one hydraulically confining lithologic zone that overlies this layer and the neutron moisture probe data indicate that values of storage coefficient range from 0.18 to 0.35 (Olmsted and others, 1973, p. 109).

CHAPTER III. GROUNDWATER FLOW SYSTEM

Conceptual Model of the Groundwater Flow System

Groundwater flow within the Yuma area is very complex because of its close interrelationship with the surface water system. In general, groundwater flows from the north to south-southwest, except beneath the Yuma Mesa where groundwater flows radially away from a prominent groundwater mound (Figure 14). Recharge to the groundwater system is predominately from agricultural irrigation, unlined canals, the Colorado and Gila rivers at high flood stage and to a lesser extent from precipitation and local runoff. Discharge from the groundwater system is predominately to groundwater drains, the Colorado and Gila Rivers at normal stage levels, phreatophyte growth in the river valleys and groundwater pumpage. Groundwater enters the Yuma area as underflow at two locations, beneath Laguna Dam and at Dome Narrows and exits the area into Mexico to the west beneath the Colorado River and to the south towards the Altar Desert.

The northern portion of the groundwater system within the Yuma area has been changed from historic conditions by the construction of the All-American canal. This unlined canal flows across sandy alluvium from east to west and created a groundwater mound which altered the natural flow from a historical westwardly direction to a southerly direction away from the canal (Olmsted and others, 1973). The eastern portion of the groundwater system is bounded by the Gila and Tinajas Altas mountains. Groundwater in this area generally flows from north to south through the Fortuna Basin exiting the United States east of the boundary hills. The western portion of the groundwater system extends into the Mexicali Valley in Baja California, Mexico and the southern boundary extends into the Altar Desert in Sonora, Mexico.

The groundwater mound beneath the Yuma Mesa is a unique hydrogeologic feature and has an important impact on groundwater flow within the Yuma area. The groundwater mound was created by extensive agricultural development on the Yuma Mesa since 1924 (Iakisch and Sweet, 1948). Prior to the development of the mound, groundwater flowed from north to south across the Yuma Mesa according to a groundwater elevation map from 1925 (Olmsted and others, p.89). The first measured increases in groundwater levels beneath the Yuma Mesa occurred after

1939 (Olmsted and others, 1973, p 86). Since that time, the mound has risen approximately 60 feet, substantially altering the historical direction of groundwater flow. Groundwater now flows radially away from the mound in all directions (Figure 14).

The vertical hydraulic interconnection between the upper, fine-grained zone, Clay B and the coarse-gravel zone is very important within the Yuma area. The saturated sediments essentially act as one unconfined to semi-confined aquifer. Water level elevations from wells completed within each water-bearing zone indicate a general downward gradient, however, elevation differences between each zone are generally less than one foot.

Water level elevations respond and equilibrate rapidly whenever an external stress is applied to the aquifer. For example, when a well pumps water from the coarse-gravel zone, water levels in the overlying upper, fine-grained zone respond to the pumping within minutes and begin to decrease in elevation. Once the cessation of pumping occurs in the lower coarse-gravel zone, water levels in both zones equilibrate to their original elevation in less than an hour (ADWR, 1992). This can be attributed to the highly transmissive nature of the sediments and the extremely high vertical hydraulic interconnection between each of the layers. As previously discussed, Harshbarger (1971) estimated the vertical hydraulic conductivity at approximately 0.10 Ft/Day for the coarse-gravel zone in the western portion of the Yuma Mesa area.

Recharge

Recharge to the groundwater system is predominately from excess agricultural irrigation, leakage from unlined canals, the Colorado and Gila rivers at high flood stage and to a lesser extent from precipitation and local runoff. Since precipitation averages less than 3 inches annually within the Yuma area, very little of this water penetrates below the soil zone except perhaps in irrigated agricultural areas. This was documented by soil moisture tests conducted within the top few feet of soil by Olmsted and others (1973). However, there is enough precipitation at times to produce local runoff, especially during the rainy season in late summer. Most of the precipitation infiltrates rapidly into gravelly washes and does not reach the Colorado and Gila Rivers, providing a potential source of local recharge. The annual total un-gaged local runoff from precipitation was estimated to be less than 1000 AF/Year with a major part of this infiltrated water later evaporating and transpiring (Olmsted and others, 1973). Therefore, recharge from precipitation and local runoff was determined to be negligible (Olmsted and others, 1973, p. 72).

Agricultural Irrigation

Maximum potential recharge from agricultural irrigation was estimated for each subarea within the river valleys and Yuma Mesa. As previously discussed, the Yuma area has been divided into subareas based upon hydrogeology and irrigation district (I.D.) boundaries (Figure 15). Subareas may contain more than one irrigation district and include Yuma Valley (Yuma Valley Water Users Association), Reservation (Reservation and Bard I.D.), North Gila Valley (North Gila Valley I.D.), South Gila Valley (Yuma Irrigation District), Yuma Mesa (comprised of Yuma Mesa I.D., Unit B I.D. and Hillander C) and Mexico. Detailed data for each subarea (except Mexico) were provided by U.S. Bureau of Reclamation (U.S.B.R.) Crop Census Reports regarding crop type, total acres grown for each crop type, and water delivered to farms (U.S. Bureau of Reclamation, 1978-1989b). However, no data were available to easily determine the location of where each crop was grown within each irrigation district. Consumptive use data for each crop type were obtained from U.S. Department of Agriculture (1982).

Agricultural crop types, total acres grown and water applied data were not available for Mexico. It was assumed that the crop type mix, water applied per irrigated acre of land was similar to Yuma Valley. Therefore, when estimating the maximum potential recharge for Mexico, the recharge rate per acre developed for Yuma Valley was applied for Mexico.

The methodology used to estimate the maximum potential recharge for each subarea involved subtracting the seasonal consumptive use (C.U.) for each subarea crop type mix from the total reported water applied to each subarea. The equation used to calculate maximum potential recharge is presented below:

$$\begin{array}{l}\text{Seasonal Maximum Potential} \\ \text{Recharge per subarea (AF)}\end{array} = \begin{array}{l}\text{Total Seasonal Water} \\ \text{Delivered per subarea} \\ \text{subarea (AF)}\end{array} - \left[\begin{array}{l}\text{Individual Crop} \\ \text{Consumptive Use} \\ \text{(AF/AC)}\end{array} * \begin{array}{l}\text{Seasonal Individual} \\ \text{Cropped Acres per} \\ \text{subarea (AC)}\end{array}\right]$$

This relationship requires the quantification of total cropped acres for each season within each subarea and estimate of the total consumptive use requirement. To do this, annual cropped acreage for each crop type for each subarea was summarized between 1978 and 1989. The total reported annual cropped acres grown, which includes multiple cropping, represents one calendar year. Each crop type was then categorized seasonally, depending on when the crop is generally grown. For example, lettuce is grown only during the winter months, cotton is grown during the summer months and citrus groves are grown all year round. The winter season corresponds to October through March and summer to April through September. This breakdown gives the seasonal cropped acres for each crop type mix within each subarea.

To obtain the seasonal consumptive use requirement for each subarea, the total seasonal cropped acres for each crop type were then multiplied by the estimated consumptive use for each crop type. Table 3 gives an example of how seasonal consumptive use was obtained for each subarea using 1979 data from the Yuma Mesa I.D..

The other component of calculating the maximum potential recharge is the seasonal total water delivered to the crops for each subarea. Monthly reported water deliveries for each irrigation district (subarea) was obtained from the U.S.B.R. Crop Census Reports (U.S. Bureau of Reclamation 1978-1989b). These monthly data were summarized for 6 month periods corresponding to growing seasons (i.e., Winter = October-March and Summer = April-September).

As previously mentioned, the maximum potential recharge for each subarea was estimated by subtracting the seasonal consumptive use from the seasonal water applied. Table 4 presents the maximum potential recharge and total cropped acreage per irrigation district between 1978 and 1988. Table 5 presents the initial conceptual annual recharge rate per acre per subarea between 1978 and 1988. Yuma Mesa I.D. and Unit B I.D. have the largest estimated recharge rates within the Yuma area. This can be attributed to the coarse-grained sediments on the Yuma Mesa and the large amounts of water applied to the crops in the summer season.

There has been a change in crop types grown in the Yuma area between 1978 and 1989. This crop type change may have contributed significantly to the continuing shallow

Table 3
Method of Calculating Seasonal Consumptive Use and Maximum Potential Recharge Using Yuma Mesa I.D.

Crop Type (1)	Growing Season (2)	1979 Total Acres (1)	1979 Summer Acres (3)	1979 Winter Acres (3)	Crop Consumptive Use (4)	1979 Summer Season Consumptive Use (5)	1979 Winter Season Consumptive Use (5)
Soybeans	Winter	60		60	1.9 AF/AC		114
Alfalfa Hay	Both	1,740	870	870	6.2 AF/AC	5,394	5,394
Cotton	Summer	300	300		3.5 AF/AC	1,050	
Lemons & Limes	Both	8,100	4,050	4,050	4.0 AF/AC	16,160	16,160
Grapefruit	Both	885	443	443	4.0 AF/AC	1,766	1,766
Oranges/Tangerines	Both	4,850	2,425	2,425	3.3 AF/AC	7,905	7,905
Nursery	Winter	45	-0-	45	2.0 AF/AC	-0-	90
Misc. Crops	Both	450	225	225	2.0 AF/AC	450	450
Totals		16,430	8,313	8,118		32,725	31,880
Total Reported Water Delivered to Farms (1)							
October 1978 - March 1979 = 34,890 AF							34,890
April 1979 - September 1979 = 131,860 AF						131,860	
Maximum Potential Recharge Estimated (Rounded to Nearest 100 AF)						99,100 AF	3,000 AF

Notes:
(1) Data from U.S.B.R. Crop Census Reports (U.S. Bureau of Reclamation, 1978-1989b).
(2) Estimated by A.D.W.R. Agricultural Planner.
(3) Based upon growing season. If crop is grown year round, then the total acreage was divided in half.
(4) Data from U.S. Department of Agriculture (1982). If consumptive use was unknown a value of 2.0 AF/AC was arbitrarily assigned.
(5) Estimated by multiplying seasonal acres by the crop consumptive use. (Units = AF)

Table 4
Maximum Potential Recharge and Total Cropped Acres Per Irrigation District within the Yuma Area

Location	*Maximum Potential Recharge (Water Year)*										
	1978	***1979***	***1980***	***1981***	***1982***	***1983***	***1984***	***1985***	***1986***	***1987***	***1988***
Yuma Mesa I.D.	129,200	102,200	139,700	147,200	107,200	111,400	111,500	130,900	134,400	155,800	189,300
Yuma Valley W.U.A.	49,800	53,400	58,700	69,700	58,200	87,600	50,900	69,700	77,200	48,000	44,500
Reservation	8,300	12,900	11,700	16,400	14,400	10,000	1,100	11,900	15,100	13,500	14,500
Bard I.D.	9,300	11,400	13,800	17,200	11,400	7,500	5,100	17,200	12,900	15,000	12,600
North Gila Valley I.D.	22,300	20,300	19,200	24,000	19,600	18,200	15,900	24,800	19,100	12,900	27,100
Yuma I.D. (South Gila Valley)	18,200	22,700	21,300	23,200	20,100	23,400	20,700	24,200	21,900	23,800	20,800
Unit B I.D.	19,600	19,100	19,300	20,500	15,400	16,800	16,800	18,300	18,300	16,300	19,200
Total	256,700	242,000	283,700	318,200	246,300	274,900	222,000	297,000	298,000	285,300	328,000
Total Cropped Acres Per Irrigation District (Calendar Year)											
Yuma Mesa I.D.	16,060	16,430	17,031	14,386	17,982	17,694	18,069	17,922	16,820	17,401	16,629
Yuma Valley W.U.A.	54,430	55,331	61,106	58,044	59,022	55,399	66,305	65,021	68,065	70,194	78,220
Reservation	5,946	7,620	7,721	6,643	6,009	3,381	5,193	5,378	5,434	6,402	8,644
Bard I.D.	6,910	7,633	7,389	7,503	7,156	10,294	6,845	6,550	6,328	9,609	10,685
North Gila Valley I.D.	7,940	7,275	8,156	7,947	8,602	7,954	7,752	9,211	10,697	9,722	9,053
Yuma I.D. (South Gila Valley)	12,550	13,617	13,512	13,904	13,350	11,928	14,169	16,246	16,274	15,093	14,748
Unit B	3,025	2,925	2,721	2,720	2,478	2,446	2,374	2,420	2,451	2,594	2,695
Total	106,860	110,830	117,640	111,150	114,600	109,100	120,710	122,750	126,070	131,020	140,670

1. Recharge estimates rounded to nearest 100 acre-feet.
2. Cropped acres from U.S.B.R. Crop Census Reports (U.S. Bureau of Reclamation 1978-1989b). Includes multiple cropping total rounded to nearest 10 acres.
3. Water Year = October 1 → September 30

Table 5
Initial Estimated Annual Maximum Potential Recharge Rate per Acre for each Subarea within the Yuma Area for 1978 - 1988
Acre-Feet/Acre

Year	*Yuma Mesa I.D.*	*Yuma Valley Water Users*	*Reservation*	*Bard*	*North Gila Valley*	*Yuma Valley I.D.*	*South Gila Valley*	*Unit B*
1978	8.0	0.91	1.4	1.4	2.8	2.8	1.5	6.5
1979	6.2	0.97	1.7	1.5	2.8	2.8	1.7	6.5
1980	8.2	0.96	1.5	1.9	2.4	2.4	1.6	7.1
1981	10.2	1.2	2.5	2.3	3.0	3.0	1.7	7.5
1982	6.0	0.99	2.4	1.6	2.3	2.3	1.5	6.2
1983	6.3	1.6	3.0	1.8	2.3	2.3	2.0	6.9
1984	6.2	0.77	0.21	0.75	2.1	2.1	1.5	7.1
1985	7.3	1.1	2.2	2.6	2.7	2.7	1.5	7.6
1986	8.0	1.1	2.8	2.0	1.8	1.8	1.4	7.5
1987	9.0	0.68	2.1	1.6	1.3	1.3	1.6	6.3
1988	11.4	0.57	1.7	1.2	3.0	2.9	1.4	7.1
Average	**7.9**	**0.99**	**2.0**	**1.7**	**2.4**	**2.4**	**1.6**	**6.9**

Notes:

Calculated by dividing the maximum potential recharge by the total cropped acres from Table 4.

groundwater level problems within the river valleys of the Yuma area. In general, the trend has been to decrease growing cotton in favor of vegetable crops such as lettuce, broccoli and cauliflower.Figures 16 through 22 compare six major crop types grown in each of the irrigation districts within in the river valleys and Yuma Mesa. The crops are cotton, wheat, citrus, lettuce, cauliflower, and broccoli. Figure 23 presents the percent change in total acres for selected crop types between 1978 to 1989.

The increase in vegetable crops grown is important because the consumptive use of vegetable crops are several times less than the required water applied per acre to successfully grow the crop. Certain vegetables require additional water for germination and quality control for marketability purposes. This additional water generally ranges between one and 2.44 AF/AC depending upon the vegetable (ADWR, 1991). Therefore, when estimating the maximum potential recharge from irrigating vegetables the plant's consumptive use and its additional water requirements must be considered. For example, the consumptive use of lettuce according to U.S. Department of Agriculture (1982) is 0.8 AF/AC, additional water needs are 2.44 AF/AC (ADWR, 1991) and the water required to grow the crop in the Yuma Valley is approximately 4-6 AF/AC (Personal Communication, Don Pope, Manager, Yuma County Water Users' Association). Therefore, the total water requirement is about 3.2 AF/AC and the maximum potential recharge rate per acre for growing lettuce is approximately 1-3 AF/AC. This combination indicates there may be substantial amounts of water available for deep percolation recharge to the groundwater system where vegetables are grown.

Canal Seepage

Canal seepage was estimated for 14 canals in the Yuma area within both the United States and Mexico. The canals in the river valleys include the All-American, Gila Gravity Main, Yuma Main, South Gila Main, North Gila Main, Central, East and West Main. The canals on the Yuma Mesa include the A and B and 242 Lateral. Canals in Mexico include Alamo, Alamo Del Norte and La Principal (Figure 24). Most of these canals are unlined except for those on the Yuma Mesa and a portion of the La Principal canal. One major canal in the Yuma area that was not considered is the Main Outlet Drain Extension (MODE) since it is lined with concrete throughout the Yuma area.

Construction data for the canals located in the United States were obtained from a project data publication by the U.S. Department of Interior (U.S. Department of Interior, 1981). This report contained canal dimension data including bottom width, side slope ratio, average water depth, total lineal length and dates of construction. Data for the canals in Mexico were obtained from a field trip conducted in February 1990 across northern Sonora and eastern Baja California. Estimated average canal width, water depth and lining status were documented during this field trip. Table 6 summarizes the construction characteristics of the primary canals in the Yuma area.

Canal seepage losses for each irrigation district are reported in the U.S. Bureau of Reclamation Crop Census Reports. These monthly data represent total losses from all water deliveries within the irrigation district and are not necessarily reflective of any one canal. Seasonal total seepage losses and recharge rates per mile for each major canal are summarized in Table 7.

Initial estimates of infiltration rates for each canal were obtained from various sources. Infiltration rates for the All-American, Gila Gravity and Yuma Main canals were estimated based upon seepage losses reported in Olmsted and others (1973) and their construction characteristics. A seepage test was conducted on the East Main canal in 1954 (YCWUA, 1954). Initial estimates for the remainder of the canals were adopted from U.S. Geological Survey (1980).

Initial estimates of infiltration rates were calculated for the All-American, Gila Gravity and Yuma Main canals using Darcy's Law. Darcy's Law states the Q = KIA, where Q is the estimated seepage (FT^3/DAY), K is the hydraulic conductivity (FT^2/DAY), I is the hydraulic gradient (FT/FT), and A is the wetted area (FT^2) of the canal. Olmsted and others (1973) estimated an annual seepage rate per lineal length for the All-American and Gila Gravity Main canals. Wetted area per lineal length of canal was estimated using the bottom width, average water depth and side slope ratio data provided by the U.S. Department of Interior (1981). Vertical hydraulic conductivity was then estimated by dividing the seepage rate per lineal length by the wetted area per lineal length of canal assuming a unit gradient of 1:1.

The annual seepage rate for the Yuma Main canal was estimated by comparing gaging data at the canal inflow and outflow locations. Diversions from the All-American canal represent the total inflow into the Yuma Main canal. Gaged outflows from the canal include the wasteway into the Colorado River and the Yuma Main below the Colorado River siphon. The difference between the inflow and these two gaged outflows equals the maximum potential volume of water available for canal seepage. However, this does not take into account any small diversions upstream from these two gaged outflows. An initial estimate of vertical hydraulic conductivity was calculated using this maximum potential seepage rate and the wetted area per lineal length of the canal assuming a unit gradient of 1:1.

Table 6
Construction Data for Major Canals Within the Yuma Area

Canal	*Lining Status*	*Bottom Width (Feet)*	*Side Slope Ratio*	*Average Water Depth (Feet)*	*Total Length (Mile)*	*Diversion Capacity (Ft ^{3}/Sec)*
All American (3)	Unlined	160	1.75:1	21	(80) 26	15,155
Gila Gravity (3)	Unlined	22	2:1	13	(20.5) 11.2	2,200
Yuma Main	Unlined	50	1.25:1	9	3.5	2,000
Reservation Main	?	?	?	?	3.25	220
East Main	Unlined	25	2.75:1	5	24	450
West Main	Unlined	20	1.25:1	6	21.4	500
Central	Unlined	20	1.25:1	5	12.35	200
North Gila (3)	Unlined	42	2:1	3	(10.2) 5.6	200
South Gila	Concrete	5	1.5:1	4	7.7	282
"A" Canal	Concrete	8	1.5:1	10	13.6	620
"B" Canal	Concrete	8	1.5:1	6	9.3	280
Alamo Del Norte (4)	Unlined	50	?	5	(4.6)	Unknown
Alamo (4)	Unlined	100	?	5	(6.9)	Unknown
La Principal (4)	Concrete (unlined)	300 (100)	?	5	(14.9)	Unknown

Notes:

(1) All data from U.S. Bureau of Reclamation Project Data Report unless otherwise noted (U.S. Department of Interior, 1981).
(2) Construction data represent canal dimensions at initial diversion point only. They do not reflect downsizing along entire length of canal.
(3) Numbers in parenthesis show the total length if canal exists outside the model boundaries.
(4) Construction data for Mexico canals were estimated from a field trip and air photos and may not necessarily reflect actual canal conditions. Total lengths are unknown and were estimated only within model boundaries.

Table 7
Initial Estimates of Canal Seepage Losses and Recharge Rates per Mile

Location	*Water Years (Acre-Feet)*										*Maximum Potential Recharge Rate/Mile (7)*
	1979	***1980***	***1981***	***1982***	***1983***	***1984***	***1985***	***1986***	***1987***	***1988***	
All American (1)	112,000	112,000	112,000	112,000	112,000	112,000	112,000	112,000	112,000	112,000	4,300
Gila Gravity (2)	22,400	22,400	22,400	22,400	22,400	22,400	22,400	22,400	22,400	22,400	2,000
Yuma Main (3)	6,970	10,670	10,920	10,300	6,180	9,000	4,430	11,350	12,950	10,190	2,700
East & West Main, Central (4)	46,360	46,450	53,990	44,450	26,640	33,890	49,570	49,710	48,600	27,000	740
South Gila Main (4)	1,200	880	1,410	1,070	960	860	700	700	840	510	120
North Gila Main (4)	740	0	3,110	4,810	4,940	3,840	7,560	10,720	9,620	10,150	990
Yuma Mesa Canals (4 & 5)	13,020	15,850	18,780	16,480	13,400	16,100	18,750	16,920	6,360	6,400	620
Mexico (6)	42,600	42,600	42,600	42,600	42,600	42,600	42,600	42,600	42,600	42,600	Unknown

Notes:

Water Year: October → September. For example Water Year 1979 = October 1978 → September 1979

(1) Estimated assuming 4,300 AF/Year/Mile (Olmsted & Others, 1973) and 26.03 miles within model boundary.
(2) Estimated assuming 2,000 AF/Year/Mile (Olmsted & Others, 1973) and 11.17 miles within model boundary.
(3) Estimated from gaging data - Gage #09524000; #09525500; #09525000, (Diversion at All-American - Waste to Colorado River -below Siphon.)
(4) Data from U.S.B.R. Crop Census Reports (U.S. Bureau of Reclamation, 1978-1989b)
(5) Includes Yuma Mesa I.D. and Unit B I.D. data from U.S.B.R. Crop Census Reports (U.S. Bureau of Reclamation, 1978-1989b).
(6) Estimated assuming infiltration rate of 0.85 Ft/Day for each canal (U.S. Geological Survey, 1980).
(7) Maximum potential recharge rate per mile estimated by dividing the 10 year total of canal seepage loss by total length of each canal. Lengths of each canal were estimated from U.S.G.S. 7.5' quadrangle maps. Values rounded to nearest 10 Acre-Feet/Mile.

Discharge

Groundwater Pumpage

Groundwater is pumped within the Yuma area for a wide variety of purposes including irrigation, drainage, regulatory, municipal and domestic. However, groundwater is pumped predominantly for irrigation and drainage with over 60 percent attributed to irrigation between 1978 and 1989. Groundwater is pumped for drainage purposes to lower the water table in the river valleys. The drainage wells generally discharge into nearby drainage canals. Groundwater pumpage for regulatory purposes include the 242 well field along the Southern International Boundary on the Yuma Mesa east of San Luis, Arizona which became operational in 1981 (U.S. Bureau of Reclamation, 1978-1989a). These wells were constructed in accordance with Minute 242 of the Treaty of 1944 and were designed to intercept groundwater flowing south into Mexico. The wells discharge water into the "242 Lateral" that flows into Mexico near San Luis, Sonora. Wells constructed for monitoring purposes are used for obtaining both water quality and water level elevation data. These wells are primarily operated and maintained by the U.S. Bureau of Reclamation.

Most of the water production wells used for irrigation, drainage, municipal and regulatory purposes are constructed with screened openings completed in the coarse-gravel and upper wedge zones. The total depth of these wells are generally less than several hundred feet below land surface. Wells used for monitoring purposes are constructed with screened openings completed in the overlying upper, fine-grained zone with a total depth generally less than a hundred feet below land surface. Pumpage for domestic purposes was not simulated since no data existed regarding total volumes or locations and it was considered to be insignificant.

Groundwater pumpage data within the United States and Mexico were obtained from two different sources. Data for the United States were obtained from the U.S.B.R. Ground Water Status Reports (U.S. Bureau of Reclamation, 1978-1989a). These reports provide data for individual wells and include reported annual pumpage, cadastral location, name of owner, and well use. However, wells used for domestic purposes are not reported in these reports.

Groundwater pumpage data for Mexico were provided by the International Boundary and Water Commission (I.B.W.C.). Data obtained for Mexico did not include individual wells, only annual totals for the Mexicali and Sonora valleys and the Mesa Arenosa well field located east of San Luis, Sonora. The total number of individual wells pumping groundwater within the Mexicali and Sonora valleys is unknown but is approximately 500 (Earl Burnett, U.S. Bureau of Reclamation, Personal Communication).

Total annual pumpage within the United States portion of the Yuma area has increased 40 percent between 1978 and 1989, from approximately 217,000 AF to 303,700 AF. The total annual pumpage within Mexico has increased by approximately 16 percent, from 718,000 AF to 833,700 AF (Table 8).

Evapotranspiration

Native floodplain vegetation consumes a large amount of water along the Colorado River within the Yuma area. The vegetation is predominantly phreatophytes which obtain their source of water from shallow groundwater (McDonald and Hughes, 1968). The types of phreatophyte vegetation along the Colorado River from Mexico to Davis Dam north of Yuma were mapped for the years 1981 and 1986 (Younker and Anderson, 1986). The predominant types of phreatophytes identified in 1986 between the Southern International boundary and Laguna Dam along the Colorado River were salt cedar, cottonwood, willow, screwbean and honey mesquite, arrow weed and creosote and with approximately 8,400 acres mapped in 1986 and approximately 7,500 acres in 1981 (Younker and Anderson, 1986). According to Raymond and Rezin (1989) salt cedar has generally replaced mesquite as the predominant phreatophyte plant type along the lower Colorado River.

Rates of water use by phreatophytes vary greatly due to the influence of various factors which include vegetation type, depth to groundwater, solar radiation, relative humidity and wind (McDonald and Hughes, 1968). According to Graf (1980), depth to groundwater is the single most important controlling factor in phreatophyte growth. If the depth to water is less than 20-30 feet, phreatophytes will flourish. As previously discussed, groundwater is relatively shallow throughout the entire Yuma area, so phreatophyte growth is prolific.

Table 8
Total Annual Pumpage in the Yuma Area
Acre-Feet

Calendar Year	*Mexico*		*United States*	
	Sonora and Mexicali Valley	*Mesa Arenosa Well Field*	*Arizona and California*	*Regulatory 242 Well Field*
1978	613,770	104,290	216,910	0
1979	574,310	27,770	233,750	0
1980	532,640	16,980	258,900	1,870
1981	698,010	142,360	244,980	20,000
1982	644,000	147,630	237,780	22,730
1983	447,000	18,580	218,180	3,230
1984	466,170	7,320	241,360	3,120
1985	535,790	30,210	248,520	2,510
1986	504,000	10,730	253,280	4,720
1987	557,850	41,620	248,110	6,010
1988	620,490	127,210	270,130	4,620
1989	694,120	139,610	269,590	34,080

Notes:

1. USA data provided by U.S. Bureau of Reclamation (1978-1989a)
2. Mexico data provided by International Boundary and Water Commission (IBWC, 1989)
3. All data rounded to nearest 10 Acre-feet

The phreatophyte plant types that consume the most groundwater are the salt cedar and cottonwood-willow assemblage. They were estimated to consumptively use 3.9 Ft/Yr at Parker Valley along the lower Colorado River upstream of Yuma (Raymond and Rezin, 1989). However, this same plant type was estimated to consume 6-7 Ft/Yr along the Gila River, near Phoenix (Gay and Hartman, 1982). The climatic conditions of the lower Colorado River are more extreme than the Gila River which would indicate more water use contrary to the estimates developed by Raymond and Rezin (1989).

The maximum potential volume of water used by phreatophytes within the Yuma area was estimated for 1986 and was made using several assumptions. First, it was assumed that all phreatophyte acreage estimates were covered with 100 percent salt cedar, cottonwood-willow assemblage. This plant community was selected since it has the highest consumptive use of the major plant types. Second, the total phreatophyte acres estimated by Younker and Anderson (1986) were multiplied by the range of consumptive use estimates of 3.9 - 6 Ft/Yr. This method estimates that approximately 29,000 to 45,000 AF of groundwater were consumptively used by phreatophytes in 1981 and 33,000 to 50,000 in 1986 along the Colorado River between Mexico and Laguna Dam.

Groundwater Discharge to Drains

An extensive canal drainage network exists throughout the river valleys and Yuma Mesa within the Yuma area (Figure 25). The drains located in the river valleys intercept shallow groundwater and discharge into the Colorado and Gila Rivers. The Yuma Mesa Outlet drain is supplied by 12 drainage wells along the Yuma Mesa/Yuma Valley escarpment which intercept groundwater flowing from the mesa towards the valley. The major drains within the Yuma area are Reservation Main and Araz in the Reservation subarea, Bruce Church, Drain No. 1 in North Gila Valley, Drainage Pump Outlet Channel (DPOC) drains in South Gila Valley, the extensive network within the Yuma Valley and the Yuma Mesa Outlet drain.

Discharge data for all the drains were obtained from several sources. The U.S. Bureau of Reclamation Ground Water Status reports contain the total discharge volumes for each subarea which do not necessarily represent individual drains (U.S. Bureau of Reclamation, 1978-1989a). Calendar year data for the drains located in the South and North Gila Valley's were obtained from these reports. The International Boundary and Water Commission (I.B.W.C.) provided monthly data for the remainder of the major drains within the Yuma area. Table 9 contains the discharge volumes of the major drains within the Yuma area from 1978 through 1989.

Table 9
Summary of Discharge from Major Drains per Subarea
(Acre-Feet)

Subarea	*Source*	*Water Year*											
		1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
North Gila Valley													
Drain #1	USBR	2,752	3,982	6,742	4,383	3,577	7,016	8,945	5,779	6,425	3,370	2,122	2,088
South Gila Valley													
DPOC 1-4	USBR	54,930	54,260	65,930	62,330	51,920	65,000	65,010	59,070	62,020	51,330	56,350	46,790
Reservation													
Reservation Main	#09530000 (IBWC)	41,098	31,144	43,166	49,022	43,547	33,331	43,137	45,376	57,368	55,245	42,716	45,359
Araz (Drain #8-B)	#09530500 (IBWC)	820	1,347	3,538	4,564	3,541	4,174	7,465	8,032	10,859	10,219	5,842	4,974
Yuma Mesa													
Yuma Mesa Outlet	#09530200 (IBWC)	32,063	18,919	22,170	25,889	29,126	18,635	19,091	31,364	23,084	17,792	22,914	24,356
Yuma Valley													
Yuma Main Drain	IBWC	74,714	75,287	91,241	91,667	76,603	76,717	99,686	96,315	109,385	104,369	95,390	95,300
TOTAL		**206,400**	**184,900**	**232,800**	**237,900**	**208,300**	**204,900**	**243,300**	**245,900**	**269,100**	**242,300**	**225,300**	**218,900**

Notes:

USBR = U.S. Bureau of Reclamation Ground Water Status Reports (U.S. Bureau of Reclamation, 1978-1989a) (Calendar Year Data)
IBWC = International Boundary and Water Commission Western Water Bulletins (I.B.W.C. 1977-1989) (Monthly Data)
Total Figures rounded to nearest 100 AF

Colorado and Gila River Interaction with Groundwater System

The Colorado and Gila Rivers act as natural drains between Laguna and Morelos Dams during normal flow conditions. During normal flows, the river stage elevation is below the groundwater elevation in the adjacent aquifer indicating groundwater discharges into the river. However, during flood flows the river stage elevation is above the groundwater elevation and the natural direction of groundwater flow is reversed and the river becomes a source of recharge.

Quantification of the hydrologic interconnection between the Colorado River and groundwater system within the Yuma area was attempted using the water budget methodology. The water budget methodology is based upon defining the total inflows and outflows along a specific reach of the river and assuming the difference between inflows and outflows is the gain or loss of the river to the groundwater system. The water budget methodology is reliant upon sufficient stream gaging data to accurately quantify the total inflows and outflows. Stream gaging locations along the main river channels include Laguna Dam, Dome Narrows, Yuma Gage, Northern International Boundary (N.I.B)., Morelos Dam, Eleven Mile Gage and the Southern International Boundary (S.I.B.) (Figure 26). Gaged inflows into the Colorado and Gila Rivers between Laguna and Morelos Dams include the Bruce Church drain, Drain No. 1 and 3, DPOC drains, Reservation Main drain, Yuma Main canal wasteway, Yuma Waste Water Treatment Plant, Yuma Mesa Outlet drain, Araz drain, Pilot Knob Power Plant and Wasteway, and Cooper wasteway (Figure 25). Gaged inflows into the Colorado River between Morelos dam and the Southern International Boundary on the United States side only include the Eleven Mile and Twenty-One Mile wasteways. There are no gaged inflows for the Mexican side of the river.

When comparing stream gaging data it is important to recognize the magnitude of the flows and the error in the flow measurements. The estimated error from each stream gage within the Yuma area was provided by the U.S. Geological Survey (Curt Webb, U.S. Geological Survey, Personal Communication). Stream gage accuracy varies between 5 percent to greater than 15 percent within the Yuma Area. A stream gage is most accurate when the cross-sectional area remains constant such as a concrete lined canal. However, the stream gages on the Colorado and Gila Rivers are only accurate to within 10-15 percent. Table 10 presents the relative accuracy of the primary stream gages within the Yuma area.

Table 10
Relative Accuracy of Stream Gages in the Yuma Area

Gage Name	*Gage No.*	*Rating (1)*	*Percent Error (2)*	*Annual Average Flow AF/Year (3)*
Laguna Dam	09429600	Good	~10%	3,193,900
Dome Narrows	09520500	Poor-Fair	>15% - ~15%	485,400
Yuma Gage	09521100	Good	~10%	3,902,800
N.I.B.	09522000	Good	~10%	6,658,700
Morelos Dam	09522030	Fair-Good	~15% - ~10%	2,177,800
S.I.B.	09522200	Poor	>15%	4,503,600

Notes:

1. Rating from U.S. Geological Survey (Curt Webb, U.S. Geological Survey, Personal Communication)
2. Percent error from Boner and others (1991)
3. Average annual flow was estimated between water year 1978 and 1989, data from Table 11.

The surface water system was divided into 3 segments in an attempt to quantify the hydrologic interconnection between the Colorado and Gila Rivers and the groundwater system. These segments include; from Laguna Dam and Dome Narrows downstream to the Yuma Gage, from Yuma Gage downstream to Morelos Dam, and from Morelos Dam downstream to Southern International Boundary. All gaged inflows and outflows were summarized in Table 11.

Using the water budget methodology for each of the three river segments between 1978 and 1989, the stream gage data indicate that upstream of the Yuma Gage the aquifer discharged approximately 189,000 AF to the Colorado and Gila Rivers, between the Yuma Gage and Morelos Dam the river lost approximately 250,000 AF to the aquifer and downstream of Morelos Dam, the aquifer discharged approximately 196,000 AF to the river. Each of these estimated groundwater discharge volumes is less than one percent of the total streamflow past the gages and is well within the stream gaging accuracy. Therefore, quantification of the hydrologic interconnection using the water budget methodology has limitations within the Yuma area and was not used.

Table 11
Surface Water Gaging Data Between Laguna Dam and Southern International Boundary for Water Years 1979-1989
(Acre-Feet)

LOCATION	*GAGE # (2)*	*1979*	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*	*1986*	*1987*	*1988*	*1989*
LAGUNA DAM TO YUMA GAGE												
Colorado R. @ Laguna Dam	429600	296,800	766,700	658,100	352,500	5,555,100	10,843,400	7,497,600	5,623,400	2,588,200	512,100	439,400
Gila R. @ Dome Narrows	520500	1,037,200	1,899,400	377,900	6,100	571,700	620,200	779,400	21,700	10,000	5,300	10,700
North Gila Drains	USBR[1]	3,980	6,740	4,380	3,580	7,020	8,950	5,780	6,430	3,370	2,120	2,090
South Gila Drains	USBR[1]	54,260	65,930	62,330	51,920	65,010	65,000	59,070	62,020	51,330	56,350	46,790
Reservation Main Drain	523000	36,140	43,170	49,020	43,550	33,330	43,140	45,380	57,370	55,250	42,720	45,360
Yuma Main Canal Waste	525000	67,650	12,360	61,280	133,450	38,260	7,290	9,390	10,620	9,770	368,440	362,350
YUMA GAGE TO NORTHERN INTERNATIONAL BOUNDARY												
Colorado R. below Yuma Main Wasteway (Yuma Gage)	521100	1,357,400	2,712,500	1,312,100	639,700	6,271,300	11,434,800	8,491,400	5,857,400	2,832,600	1,073,300	948,800
Yuma Mesa Outlet Drain	530200	18,920	22,170	25,890	29,130	18,640	19,090	31,360	23,080	17,790	22,910	24,360
ARAZ Drain	530500	1,350	3,540	4,560	3,540	4,170	7,470	8,030	10,860	10,220	5,840	4,970
Yuma Wastewater Treatment Plant	USBR[2]	5,790	5,460	5,990	6,670	6,390	6,740	7,540	7,200	7,980	9,600	9,600
Pilot Knob Wasteway & Power Plant	527000	1,064,550	3,059,930	2,244,270	716,540	2,989,400	5,119,260	4,595,520	4,931,240	3,360,890	1,562,050	523,700
MORELOS DAM TO SOUTHERN INTERNATIONAL BOUNDARY												
Colorado R. @ Northern International Boundary	522000	2,510,000	5,849,970	3,621,500	1,412,100	9,353,400	16,596,100	13,026,100	10,613,800	6,131,400	2,594,800	1,536,100
Cooper Wasteway	531850	930	900	830	760	690	820	740	880	1,300	1,070	1,470

Table 11 (continued)

LOCATION	*GAGE # (2)*	*1979*	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*	*1986*	*1987*	*1988*	*1989*
Colorado R. @ Morelos Dam to Mexico	522030	1,852,100	2,567,700	2,072,800	1,390,000	2,371,900	2,892,400	2,514,800	2,696,200	2,120,900	1,974,300	1,502,400
Colorado R. below Morelos Dam	IBWC (3)	658,900	3,283,500	1,549,800	23,100	6,990,200	13,710,300	10,512,700	N/D (4)	N/D	N/D	N/D
11 Mile Wasteway	532500	1,160	1,140	1,390	1,430	1,350	1,440	1,570	1,820	2,810	2,680	3,490
21 Mile Wasteway	533000	-0-	-0-	40	510	200	10	90	1,980	2,190	1,720	1,200
Colorado R. @ Southern International Boundary	522200	543,400	3,140,600	1,512,300	5,600	6,860,200	13,686,300	10,531,900	8,255,700	4,190,700	783,300	29,300

Notes:

(1) All data from U.S. Geological Survey (HYDRODATA) or International Boundary and Water Commission (IBWC) Western Water Bulletins. All data rounded to nearest 10 AF, except Colorado and Gila River flows rounded to nearest 100 AF.

(2) All gage numbers begin with a "09".

(3) $USBR^1$ = Data from USBR Ground Water Status Reports (calendar year data). $USBR^2$ = Data from U.S. Bureau of Reclamation (calendar year data). IBWC = Data from IBWC Western Water Bulletins.

(4) N/D = No data available.

Underflow

Groundwater enters the Yuma area as natural underflow in two locations. One location is along the Colorado River between the Chocolate and Laguna Mountains beneath Laguna Dam and the other is along the Gila River between the Laguna and Gila Mountains at Dome Narrows (Figure 3). Groundwater exits the United States as underflow to the west-southwest along the Colorado River between Morelos Dam and the Southern International Boundary (S.I.B.) and to the south along the international boundary with Mexico. Groundwater exiting to the west-southwest beneath the normally dry Colorado River flows towards the major agricultural region in Mexicali Valley, Baja California. Groundwater exiting to the south along the Southern International Boundary flows from the mound beneath the Yuma Mesa towards the Mesa Arenosa well field in Sonora, Mexico on the west side of the boundary hills and from the Fortuna Basin towards the Altar Desert on the east side of the boundary hills (Figure 3).

The total volume of groundwater within the upper several hundred feet of saturated sediments entering or exiting the Yuma area was estimated by different methodologies. The volume of water entering the Yuma area as natural underflow was estimated by Olmsted and others (1973) by assuming the basin geometry, transmissivity and the water level gradient. Olmsted and others (1973) estimated underflow at 700 AF/Year and 1000 AF/Year for Laguna Dam and Dome Narrows, respectively. Underflow out of the United States was estimated using flow nets which were constructed using geologic data provided by drill logs, estimates of transmissivity and water level elevations from 1978, 1983 and 1989. Water level elevations between Morelos Dam and the S.I.B. changed significantly due to the flooding in 1983-84 and have an impact on the estimate of underflow leaving the United States. Increased water level gradients along the Southern International Boundary increased the estimated volume of underflow by approximately 10-15 percent. The total annual volume of underflow exiting the United States into Mexico between the Morelos Dam and S.I.B. to the west-southwest was estimated at 37,000 AF/Year and 41,000 AF/Year for 1978 and 1983, respectively. The total annual volume of underflow exiting the United States into Mexico along the Southern International Boundary was estimated at 95,000 AF/Year and 109,000 AF/Year for 1978 and 1983, respectively. Underflow estimates using water level elevation data for 1989 were identical to 1983. Therefore, estimates from 1983 were considered representative for the period of 1983 to 1989. However, underflow is significantly affected by wellfield pumping in Mexico and the United States which changed significantly in 1983 because of the Colorado River flooding (Table 8).

Change in Storage

The U.S. Bureau of Reclamation (U.S.B.R.) estimates the annual change of groundwater in storage for the agricultural regions within each subarea. These estimates are based upon the annual change in groundwater level maps published in the Ground Water Status Reports and a constant value of specific yield (i.e., 15 percent) (U.S. Bureau of Reclamation, 1978-1989a). The maps represent the annual change in groundwater levels using December water level data and are reflective of the upper, fine-grained zone only. The data do not include the Fortuna Basin or any parts of Mexico and are of little use for modeling purposes since the model domain covers significantly more area than represented by these estimates.

The Yuma area has experienced an increase of groundwater in storage of approximately 19,000 AF between 1978 and 1989 according to the Ground Water Status Reports (U.S. Bureau of Reclamation, 1978-1989a). The Yuma Valley has experienced an increase in storage of approximately 13,300 AF which is a reflection of the shallow water level problems this part of Yuma has been experiencing for the last 10 years. However, the Yuma Mesa was estimated to have experienced a decrease of groundwater in storage of approximately 5,600 AF between 1978 and 1989 (U.S. Bureau of Reclamation, 1978-1989a).

CHAPTER IV. SURFACE WATER FLOW SYSTEM

Conceptual Model of the Surface Water Flow System

There are several major components to the surface water flow system in the Yuma Area. These include the Colorado and Gila Rivers, All-American canal, Gila Gravity Main canal and an extensive drainage canal network (Figure 3). The Colorado River enters the Yuma area at Laguna Dam between the Chocolate and Laguna Mountains and flows south. The Gila River enters the Yuma area at Dome Narrows between the Laguna and Gila Mountains and flows west towards its confluence with the Colorado River just east of the city of Yuma. The Colorado River then flows southward and creates the international boundary between Arizona and Baja California, Mexico. The modern Colorado River is now entirely diverted into Mexico at Morelos Dam, just downstream of the Northern International Boundary. The normally dry Colorado River downstream of Morelos Dam now only flows during flood stages. The Colorado River acts as a natural groundwater drain at normal flows, but can be a source of recharge during flood stages.

The All-American canal diverts water from the Colorado River at Imperial Dam several miles upstream of Laguna Dam outside of the Yuma area. The All-American canal flows west towards the Imperial Valley in California. This canal supplies water to several irrigation districts including the Imperial, Reservation and Bard Irrigation Districts within California and the Yuma County Water Users Association in Arizona.

There are several major diversions from the All-American canal within the Yuma area. The Yuma Main canal diverts water passes through the Fort Yuma Indian Reservation and flows south under the Colorado River via an inverted siphon and supplies water to the City of Yuma and Yuma Valley in Arizona (Figure 24). The Yuma Main canal splits into the East Main and West Main canals along the northern end of the Yuma Valley. The East Main canal flows along the foot of the Yuma Mesa escarpment on the east side of Yuma Valley and joins the West Main canal at the southern end of the valley. The West Main canal flows on the west side of Yuma Valley and joins the East Main canal near San Luis, Arizona where the remaining water left in either canal jointly flows into Mexico.

The Gila Gravity Main canal also diverts water from the Colorado River at Imperial Dam upstream of Laguna Dam outside of the Yuma area. The Gila Gravity Main canal flows south in Arizona on the east side of the Yuma area along the foot of the Laguna Mountains towards the Yuma Mesa Pumping Plant.

There are several diversions from this canal within the Yuma area prior to reaching the Yuma Mesa Pumping Plant. The North Gila Main canal supplies water to the North Gila Valley Irrigation District and South Gila Valley subareas via the North Gila Main and South Gila Main canals, respectively (Figure 24). The Wellton-Mohawk canal also diverts water prior to the pumping plant, however this canal supplies water to the Wellton-Mohawk Irrigation District east of the Gila Mountains outside of the Yuma area. The Gila Gravity Main canal ends at the Yuma Mesa Pumping Plant and supplies water to both the A and B Canals on the Yuma Mesa.

An extensive drainage canal network exists throughout the river valleys and Yuma Mesa (Figure 25). The drains located in the river valleys intercept shallow groundwater and flow to the Colorado and Gila Rivers except for the Yuma Valley Main drain. This drain flows into Mexico near San Luis, Sonora at the southern end of the Yuma Valley. The Yuma Main Drain is comprised of at least seven secondary drains which include the North, East, Gardenshire, Southeast, Stub No. 2, Southwest and South. The Yuma Main drain collects water from these drains which is then pumped into Mexico at the Yuma Valley Pumping Plant at the southern end of the valley.

Other major drains in the Yuma area include the Reservation Main and Araz in California, Drain #1 and Bruce Church in North Gila Valley, and the Drain Pump Outlet Channel (DPOC) drains in South Gila Valley. The Reservation Main drain flows through the Bard and Reservation Irrigation Districts of California. This drain discharges into the Colorado River near the northern end of the city of Yuma by the Fourth Avenue bridge. The Araz drain flows along the foot of the All-American canal in the Reservation Irrigation District and discharges into the Colorado River just upstream of the Pilot Knob Power Plant. The Bruce Church and Drain #1 flow through the North Gila Valley subarea discharging into the Gila and Colorado Rivers, respectively. The four DPOC drains in South Gila Valley are concrete lined and are supplied water from 23 wells located adjacent to the lined drainage canals.

The Yuma Mesa Outlet drain is a buried concrete pipe that flows north and discharges into the Colorado River near the Yuma waste water treatment plant west of the city of Yuma (Figure 25). The Yuma Mesa Outlet drain is supplied water from 12 wells located along the Yuma Mesa/Yuma Valley escarpment. These wells pump groundwater that flows east to west from the Yuma Mesa towards the Yuma Valley.

Colorado River

The Colorado River drains approximately 246,700 square miles within the western states of Wyoming, Colorado, Utah, New Mexico, Nevada, California and Arizona (Boner and others, 1991). The Yuma area is located geographically at the downstream end of the Colorado River basin where the river leaves the United States and flows into the Republic of Mexico (Figure 1).

The Colorado River acts as a natural drain to the groundwater system during normal flow conditions between Laguna and Morelos Dams. The hydraulic interconnection between the river and the groundwater system is dependant upon the river bottom elevation, river stage elevation and groundwater elevation in the adjacent aquifer. The river bottom is generally below the groundwater elevation between Laguna and Morelos Dams. During normal flows, the river stage elevation is below the groundwater elevation which indicates that groundwater normally discharges into the river between Laguna and Morelos Dams (i.e., river acting as a natural drain). However during flood flows, the stage elevation in the river is higher than the water level elevation in the aquifer. This hydraulic condition reverses the natural direction of groundwater flow and the river then becomes a source of recharge to the aquifer between Laguna and Morelos Dams. Downstream of Morelos Dam the river bottom elevation is generally above the groundwater elevation. This condition indicates that groundwater does not discharge into the normally dry Colorado River downstream of the dam.

The natural river channel between Laguna and Morelos Dams is generally between 8 and 12 feet below the adjacent floodplain and between 400 and 500 feet in width (Loeltz and Leake, 1983). The elevation of the bottom of the river channel has been modified from the high flood flows that occurred between 1983 and 1987. The river bottom was scoured deeper by an average of 2 feet between Laguna and Morelos Dams according to survey data provided by the U.S.

Bureau of Reclamation (1991). These survey data illustrate river bottom elevation profiles at approximate 1.5 mile intervals between Laguna and Morelos Dam for the years 1981 and 1986. Deepening of the river channel between Laguna and Morelos Dams has altered the hydraulic interconnection between the river and adjacent aquifer by increasing the river's ability to act as a natural drain.

Colorado River flows can be divided into pre-flood, flood, and post-flood categories for the time period between 1978 and 1989. According to gaging data at Laguna Dam which was considered representative of the flows entering the Yuma area, pre-flood river flows begin prior to 1978 and continue through March 1983 (Figure 27). These flows are characterized by an average annual flow of 518,500 AF for water years 1979 through 1982 (Table 11). Flood flows occurred between March 1983 and ended in March 1987 within the Yuma area. These flows are characterized by an average annual flow of 6,421,500 AF at Laguna Dam for water years 1983 through 1987. Post-flood river flows subsided to near pre-flood conditions after March 1987. These flows are characterized by an average annual flow at Laguna Dam of 475,800 AF for water years 1988 and 1989. The lowest annual flow at Laguna Dam was 296,800 AF in water year 1979 and the peak annual flow was 10.8 million AF in water year 1984.

There are several major diversions of the Colorado River within the Yuma area. Two major diversions occur upstream of the city of Yuma at Imperial Dam. Approximately 85 percent of the flows in the Colorado River were diverted into both the All-American and Gila Gravity Main canals between 1978 and 1989. This estimate is based upon gaging data at Imperial Dam for each of the two canals and the main river channel. The other primary diversion of the Colorado River occurs downstream of the city of Yuma at Morelos Dam. Since November of 1950, the majority of the Colorado River flows have been diverted into Mexico at Morelos Dam. Therefore, the Colorado River channel is generally dry downstream of the dam except during high flood flows.

There are several drains that discharge into the Colorado River within the Yuma area. Upstream of the city of Yuma, the North Gila Valley Main Drain No. 1 flows west and drains the North Gila Valley. DPOC Drain No. 4 flows north across the South Gila Valley and discharges into the river downstream of the confluence with the Gila River. The Reservation Main drain flows across the Reservation and Bard I.D. and discharges into the river across from the city of Yuma near the Fourth Avenue bridge. Downstream of the city of Yuma, the Araz Drain flows south across the Reservation subarea while the Yuma Mesa Outlet drain flows northward across the Yuma Valley and discharges into the river. The Cooper Wasteway diverts water from the Cooper Canal into the river just upstream of Morelos Dam. Eleven Mile and Twenty-One Mile Wasteways discharge water from the West Main Canal into the normally dry Colorado River downstream of Morelos Dam above the Southern International Boundary.

Gila River

The Gila River drains over 57,850 square miles within central Arizona and western New Mexico (Boner and others, 1991). The Gila River enters the Yuma area at Dome Narrows between the Laguna and Gila Mountains and flows approximately 9 miles before joining the Colorado River just east of the city of Yuma.

The Gila River acts as a natural drain within the Yuma area during normal flows similar to the Colorado River as inferred from groundwater elevation maps (U.S. Bureau of Reclamation, 1978-1989a). Although no survey were available, the river bottom elevation is thought to be below the groundwater elevation within the Yuma area. However, quantification of the amount of groundwater discharge into the Gila River is difficult since there is only one gaging station located at Dome Narrows. The natural river channel is generally several feet below the adjacent floodplain and approximately 75 feet wide according to U.S. Geological Survey topographical maps.

Gila River flows within the Yuma area can be divided into two distinct flooding periods between 1978 and 1989. The first event occurred between 1979 and 1981 and the second between 1983 and 1985 (Figure 28). According to gaging data at Dome Narrows, Gila River flows were only 840 AF for water year 1978. The first flood event in the Gila River occurred between January 1979 and June 1981. These flows are characterized by an average annual flow of 1,104,800 AF for water years 1979 through 1981 (Table 11). Flows within the Gila River subsided to near pre-flood conditions from June 1981 through February 1983. The Gila River began flooding again in March 1983 and continued through June 1985. This period was characterized by an average annual flow of 985,700 AF for water years 1983 through 1985

(Table 11). Flows within the Gila River after June 1985 subsided to pre-flooding conditions. These flows are characterized by an annual average flow of 11,900 AF for the water years 1986 through 1989 (Table 11).

There are several drains that discharge into the Gila River within the Yuma area between Dome Narrows and the confluence with the Colorado River. The Bruce Church flows south across the North Gila Valley and DPOC Drains No. 1-3 flow north across the South Gila Valley and all discharge into the Gila River.

All-American Canal System

Construction on the All-American canal began in 1934 and was completed in 1940 (U.S. Department of Interior, 1981). Water is diverted from the Colorado River at Imperial Dam and flows west along the northern portion of the Yuma area towards Imperial Valley, California. Approximately 74 percent of the Colorado River flows were diverted into the All-American Canal between 1978 and 1989 according to gaging data at Imperial Dam.

The All-American canal within the Yuma area is unlined and approximately 21 feet deep, 160 feet wide at the bottom and 232 feet wide at normal surface water elevation (U.S. Department of Interior, 1981). The length of the canal within the Yuma area is approximately 26 miles, however, the total length is approximately 80 miles between Imperial Dam and the western end near Calexico, California. The diversion capacity of the All-American canal is 15,155 Ft^3/sec at Imperial Dam (Table 6).

Approximately 52 percent of the total water diverted between 1978 and 1989 into the All-American canal was either used within the Yuma area or diverted back into the Colorado River according to gaging data at Imperial Dam and below Pilot Knob Power Plant and Wasteway. The All-American canal supplies water to several irrigation districts in California and Arizona within the Yuma area. The Reservation Main canal was completed in 1909 and now diverts water from the All-American canal to the Reservation and Bard Irrigation districts in California (U.S. Department of Interior, 1981) (Figure 24). The Reservation Main canal has a diversion capacity of 220 Ft^3/sec and is approximately 3.25 miles in length (Table 6). The earthen Yuma Main canal was also completed in 1909 and now diverts water from the All-American canal at the Siphon Drop Power Plant (Figure 24). The Yuma Main canal has a diversion capacity of 2,000 Ft^3/sec and is approximately 3.5 miles in length (Table 6). This canal conveys water south across the Fort Yuma Indian Reservation and under the Colorado River to the East and West Main canals in Yuma Valley, Arizona.

The East and West Main canals were completed in 1909 and supply water to the entire Yuma Valley. The East Main canal flows along the foot of the Yuma Mesa/Yuma Valley escarpment along the east side of Yuma Valley. The East Main canal is approximately 24 miles long with a diversion capacity of 450 Ft^3/sec (Table 6). The Central canal diverts water from the East Main canal approximately 4 miles downstream from its diversion from the Yuma Main canal. The Central canal flows west from the Yuma Mesa and supplies water to the center part of the Yuma Valley (Figure 24). This canal is approximately 12.35 miles long with a diversion capacity of 200 Ft^3/sec (Table 6). The West Main canal flows along the western side of Yuma Valley and is approximately 21.4 miles in length with a diversion capacity of 500 Ft^3/sec (Table 6). The East and West Main canals meet at the southern end of the Yuma Valley and any waste water left in the canals then flows into Mexico near San Luis, Sonora.

Gila Gravity Main Canal System

Construction of the Gila Gravity Main canal began in 1936 and was completed in 1939, but the first water was not available until November, 1943 (U.S. Department of Interior, 1981). Water is diverted from the Colorado River at Imperial Dam and flows south along the base of Laguna Mountains towards the Yuma Mesa Pumping Plant (Figure 24). Approximately 10 percent of the Colorado River was diverted into the Gila Gravity Main canal between 1978 and 1989 according to gaging data at Imperial Dam. The Gila Gravity Main canal in the Yuma area is unlined and approximately 13.5 feet deep and 22 feet wide at the bottom. The length of the canal is 20.5 miles with a diversion capacity of 2,220 Ft^3/sec (Table 6).

The Gila Gravity Main canal supplies water to several irrigation districts within Arizona prior to reaching the Yuma Mesa Pumping Plant. The North Gila Main canal was completed in 1912 and now diverts water from the Gila Gravity Main canal to the North Gila Valley Irrigation District. The North Gila Valley Main canal has a diversion capacity of 200 Ft^3/sec and is 10.2

miles in length (Table 6). The Wellton-Mohawk canal was completed in 1951 and diverts water from the Gila Gravity Main canal near the Gila River to the Wellton-Mohawk Irrigation District. This canal flows east of the Gila Mountains outside of the Yuma area and is not a part of this investigation. The South Gila Main canal was completed in 1965 and supplies water to the Yuma Irrigation District in South Gila Valley. This canal diverts water from the Gila Gravity Main canal near the Yuma Mesa Pumping Plant. The South Gila Main canal is lined with concrete and flows along the foot of the Yuma Mesa escarpment. The canal is 7.7 miles in length and has a diversion capacity of 282 Ft^3/sec (Table 6).

The Gila Gravity Main canal ends at the foot of the Yuma Mesa escarpment east of the city of Yuma at the Yuma Mesa Pumping Plant (Figure 24). The Yuma Mesa Pumping Plant lifts water about 52 feet from the Gila Gravity Main canal into the main canal of the Yuma Mesa distribution system (U.S. Department of Interior, 1981). This main canal divides into the A and B Canals which supply water to the Yuma Mesa and Unit B Irrigation Districts. Both canals are lined with concrete and have a combined total length of 43 miles. The A Canal was completed in 1942 and flows to the southern portion of the Yuma Mesa. This canal has a diversion capacity of 620 Ft^3/sec and a normal water depth of 10 feet (Table 6). The B Canal was also completed in 1942 and diverts water from the A Canal. This canal flows along the northern portion of the Yuma Mesa and has a diversion capacity of 280 Ft^3/sec and has a normal water depth of 6 feet (Table 6).

Drainage Canal Network

An extensive canal drainage network exists throughout the river valleys and Yuma Mesa (Figure 24). The drains located in the river valleys intercept shallow groundwater and discharge into the Colorado and Gila Rivers. Drains within the Yuma area in California include the Reservation Main and Araz Drains. The major drains located within Arizona include the Bruce Church and Drain #1 in the North Gila Valley, DPOC Drains in South Gila Valley, Yuma Mesa Outlet drain and the extensive network within Yuma Valley.

The Reservation Main drain in California is comprised of several smaller secondary drains that flow into the main drain. The drain flows along the foot of the All-American and Yuma

Main canals and discharges into the Colorado River at the northern end of the city of Yuma. The Araz Drain flows along the foot of the All-American canal and discharges into the Colorado River just upstream of the Pilot Knob Power Plant and Wasteway.

Drains within the North Gila Valley I.D. include Drain #1 and #3, and the Bruce Church. Drain #1 flows along the foot of the North Gila Main canal then turns west to discharge into the Colorado River upstream of the confluence with the Gila River. Drain #3 flows along the foot of the Gila Gravity Main canal and discharges into the Gila River, however this drain was not simulated in the model. The Bruce Church drain flows south and discharges into the Gila River.

The four DPOC drains within the South Gila Valley are concrete lined and generally flow from south to north. These lined drainage canals are supplied water from 23 wells that are adjacent to the drains. DPOC Drains No.1 through 3 discharge into the Gila River while DPOC No. 4 drains into the Colorado River upstream of the city of Yuma.

The drainage network within the Yuma Valley is very extensive and construction of the main drain dates back to 1916 (Iakisch and Sweet, 1948). The Yuma Main Drain runs the entire length of the Yuma Valley from north to south collecting water from several secondary drains. There are numerous secondary drains within the Yuma Valley, however, this investigation focused on only seven. These secondary drains include the North, East, Gardenshire, Southeast, Stub No. 2, Southwest and South (Figure 25). All the water collected within these drains flows south to the Yuma Valley Pumping Plant at the southern end of Yuma Valley. The pumping plant then lifts the water 10-12 feet which flows into the Republic of Mexico near San Luis, Sonora. Also at this location are the wasteways of the East and West Main canals and the regulatory 242 canal from the Yuma Mesa which all join and flow into Mexico.

The Yuma Mesa Outlet Drain is a buried pipe that flows north within Yuma Valley and discharges into the Colorado River downstream of the city of Yuma. This drain is supplied water from 12 wells located along the Yuma Mesa/Yuma Valley escarpment which pump groundwater that flows from east to west from Yuma Mesa towards Yuma Valley.

CHAPTER V. NUMERICAL MODEL

General Approach

The regional numerical model of the Yuma area is approximately 900 mi^2 in size and is bounded on the east by the Gila Mountains, the north by the All-American canal, and the west and south by Mexico (Figure 3). The model simulates steady-state (summer 1978) and transient-state (winter 1979 - winter 1989) surface water and groundwater flow conditions. Summer corresponds to April through September and winter to October through March. The model is quasi-three dimensional, contains four layers, and simulates all the primary surface water features including rivers, canals and drains. The model accounts for underflow into and out of the Yuma area, groundwater recharge from agricultural irrigation, evapotranspiration from phreatophyte growth, and groundwater pumpage. A detailed description of the model development is discussed below.

Selection of the Model Code

The model code selected to simulate the surface water and groundwater flow system in the Yuma area was the Modular Three-Dimensional Finite Difference Groundwater Flow Model (MODFLOW) developed by the U.S. Geological survey (McDonald and Harbaugh, 1988). Several factors influenced the selection of this model code. The factors included: 1) the modular format of MODFLOW facilitates independent examination of specific hydrologic features, 2) the code is flexible and can accommodate hydraulic interconnection between multiple hydrogeologic units, and surface water - groundwater interconnection, 3) documentation is relatively complete and comprehensive, and 4) the model has been widely used throughout the professional community and is generally accepted as a valid model to simulate groundwater flow. A detailed explanation of the mathematical theory, optional packages and solution techniques are provided in the MODFLOW documentation. Refer to McDonald and Harbaugh (1988) for a complete model description.

Model Simulation Period

The model simulates steady-state surface water and groundwater flow conditions for the summer 1978 (April through September). The Yuma area was assumed to be in steady-state in 1978 since there were no major changes in surface water inflow or outflow and little change in the volume of groundwater in storage. Steady-state model runs were conducted to refine the areal distribution of hydraulic conductivity, and provide initial model-generated starting water levels for the transient-state model. This process was conducted to ensure that the hydrologic fluxes and water level distributions are internally consistent with the model input data.

The model also simulates transient-state surface water and groundwater flow conditions between October, 1978 and March, 1989. This time period was selected since it covers pre and post Colorado River flooding during the years 1983-84.

General Features of the Model

The model was constructed using seven packages offered by MODFLOW. These packages are: Basic, Block Center Flow (BCF), Well, Recharge, Streamflow-Routing, Evapotranspiration, and Strongly Implicit Procedure. A brief description of each MODFLOW package and how they relate to modeling the hydrogeologic system of the Yuma area is presented below. The Basic package establishes the active model domain (i.e., cell type), starting water levels and discretization of time. The BCF package defines the hydrogeologic framework of the model. This package computes the conductance components and rate of movement of water between adjacent model cells and to and from storage. The Well package simulates groundwater pumpage and underflow into the groundwater system. The Recharge package simulates the areal distribution of recharge from agricultural irrigation. The Streamflow-Routing package developed by Prudic (1989) simulates all surface water features within the model including rivers, canals, and drains. The application of this module to the Yuma area is extremely involved due to the complexity of the surface water system. This package is not a true surface water flow model but rather an accounting system that tracks flow in one or more streams that interact with the groundwater system (Prudic, 1989). The Evapotranspiration package simulates groundwater withdrawal from phreatophytes along the river valleys. The Strongly Implicit Procedure (SIP) package is used to solve the large system of simultaneous linear groundwater flow equations. Refer to McDonald and Harbaugh (1988) for a complete description of each package.

The model was constructed using 6 time-steps per stress period with each stress period corresponding to 6 months (182.5 days). Stress periods were intended to correspond with agricultural growing seasons and based upon a water year (i.e., summer and winter seasons). The winter season coincides with the months October through March and the summer season with the months April through September. There are 21 stress periods simulated in the transient-state model between 1978 and 1989. The model units of length are feet and of time are days. Table 12 presents the general characteristics of the model.

Model Grid

The modeled area was divided into an orthogonal grid consisting of 86 rows and 85 columns. The total model domain is 35 miles in the east-west direction and 36 miles in the north-south direction. The model grid is irregularly spaced with the smallest model cells located within the northern Yuma valley/Yuma Mesa area. The model cells sizes range from 40 acres to 640 acres and generally correspond with the Arizona Township-Range-Section grid (Figure 29).

Model Layers

Four layers are used to represent the upper several hundred feet of Colorado River deltaic sediments within the Yuma area. As previously mentioned, there are several thousand feet of saturated non-marine and marine sedimentary rocks in the Yuma area. However, only the upper several hundred feet of these sediments are hydrologically important due to their ability to yield sufficient quantities of water to wells and very large transmissivities.

The uppermost layer, Layer One, corresponds to the upper, fined-grained aquifer underneath the Yuma Mesa and All-American canal. This portion of the upper, fined-grained zone is modeled as an unconfined aquifer. Layer Two corresponds to the thin layer of silt and clay that comprises the river valley land surface and the laterally continuous Clay B underneath the Yuma Mesa. This layer is modeled as a convertible aquifer layer that can switch from a confined to an unconfined aquifer. In general, the layer is unconfined in the river valleys and confined under the Yuma Mesa. Layer Three corresponds to the lower portion of the upper, fine-grained zone throughout the entire modeled area. This layer is also modeled as a convertible aquifer layer that can switch from a confined aquifer to an unconfined aquifer. In general, this layer is unconfined throughout most of the model except beneath the Yuma Mesa and portions of South Gila Valley where the clay content is over 100 feet thick as identified by Olmsted and others (1973). The lowermost layer, Layer 4, corresponds hydrologically to the upper part of the wedge zone and the overlying coarse-gravel zone. This layer is modeled as an unconfined aquifer throughout the entire model except underneath the Yuma Mesa and portions of the South Gila Valley where the clay content is very thick. Transmissivity remains constant in this Layer since any water level changes are very small relative to the saturated thickness of the aquifer.

The thickness of model layers 1, 2 and 3 were defined by geologic contact elevations (Figures 10, 11, and 12). These elevations were derived by discretizing various geologic maps provided in Olmsted and others (1973). Layer 4 is modeled solely by its transmissivity and therefore no thickness is assigned. The transmissivity of this layer was adopted from Olmsted and others (1973, p.81).

Boundary Conditions

The selection of proper boundary conditions is essential to the accuracy of the model. Boundary cell types define the hydrologic conditions along the model borders. Inactive model cells (i.e., no-flow cells) are those for which no groundwater flow into or out of the cell is permitted. No-flow cells in the model correspond to either bedrock outcrops (e.g., Yuma or Boundary Hills) or areas where groundwater flow is parallel to impermeable boundaries. These conditions exist on the Northern and Eastern portion of the model domain.

There are two types of active cells used in the model: variable head and constant head. Variable head model cells allow the water-level elevation in the cell to fluctuate with time.

Table 12
General Characteristics of the Yuma Area Numerical Model

Model Characteristics	*Description*	*Model Units*
Steady-state	Summer 1978 (1)	Time = Days
Transient-state	Winter 1979 - Winter 1989 (1)	Time = Days
Model Grid	86 rows x 85 columns	Length = Feet
Model Layers	4 layers of variable thickness	Length = Feet
• Layer 1 • Layer 2 • Layer 3 • Layer 4	Unconfined aquifer Unconfined/confined aquifer Unconfined/confined aquifer Unconfined/confined aquifer	
Vertical Conductance between Layers	Provided using VCONT	1/Days
Recharge	Applied to uppermost active cell	Feet/Day
Streamflow-Routing	Hydraulic interconnection of surface water features with the groundwater system in model layers 1 or 3.	
Pumpage	Derived from layer 4 only.	$Feet^3$/Day
Evapotranspiration	Extinction depth 20 feet, ground-water withdrawal from model layer 3.	Feet/Day
Horizontal Hydraulic Conductivity	Volume of water that will move in unit time under a unit gradient through a unit area (2).	Feet/Day
Storage Term	Specific Yield Storage Coefficient	Dimensionless
Model Cells	No-Flow, Constant and Variable head	40 Acres to 640 Acres
Solution Technique	Strongly-Implicit Procedure	

Notes:

(1) Winter: October - March
Summer: April - September
Example: Winter 1979 = October 1978 through March 1979

(2) Lohman (1979)

These cells comprise the active simulated region within the model domain. Underflow into the model beneath Laguna Dam and at Dome Narrows was simulated using variable head cells with a constant flux. This hydrologic condition was simulated using injection wells from the MODFLOW well package. Constant head model cells are those for which the water-level elevation in the cell is held constant at a specified elevation. Constant head cells keep the water-level elevation constant, but allow the flux into or out of the cell to change in response to changing hydraulic conditions. Constant head cells are used to simulate underflow out of the model and are located in all model layers along the extreme western (column 1) and southern (row 86) boundaries only. Figure 30 presents the location and types of model cells used the model.

Water Levels

Water level data for the Yuma area were provided by the U.S. Bureau of Reclamation (U.S.B.R.). The U.S.B.R. produces water level elevation maps of the Yuma area on a quarterly basis (i.e., March, June, September, and December) using data obtained from over 500 piezometers and monitor wells. The screened intervals of these wells are located within the upper, fine-grained aquifer (model Layer 3). There are very little water level elevation data for the underlying lower coarse-gravel zone (model Layer 4) since few piezometers or monitor wells are screened in this zone. However, there appears to be a slight downward gradient between these two zones as determined from aquifer pumping tests conducted in May 1992 (ADWR, 1992). The water level difference between these two aquifers is generally less than one foot except near major pumping wells.

Initial water levels for steady-state were obtained from the U.S.B.R. March 1978 Yuma area-wide water level elevation map (Figure 14). These groundwater elevations were assumed to be representative of steady-state conditions since they had not changed significantly over the preceeding several years. Since there was little vertical hydraulic gradient between the upper, fine-grained and underlying coarse-gravel aquifers, the same initial water level elevations were assigned to all model layers except underneath the All-American canal. The water levels in model layer one beneath the All-American canal were assumed to be perched above the regional water table although there were no direct data available.

Initial and final water level data were required for transient model simulations. Model-generated final water levels (heads) from the steady-state model were used as initial heads for the 1979-1983 pre-Colorado River flooding transient-state simulation at the recommendation of the U.S. Geological Survey. Initial heads for the 1983-1989 post-Colorado River flooding transient-state simulation were adopted from the model-generated final heads from the pre-Colorado River flooding transient-state simulation. The use of these model-generated water levels as initial heads permits the transient-state model hydraulic properties and fluxes to be internally consistent. If they are not, the computed heads in the transient model would be a function of both the initial conditions and the external stresses that are imposed (Reilly and others, 1984). This process enhanced the success of the transient modeling effort.

Ending measured water levels were used as one tool in evaluating the success of the model calibration. Figures 31 and 32 present the March 1983 and March 1989 Yuma area-wide water levels.

Aquifer Parameters

Hydraulic conductivity, transmissivity, specific yield and storativity were estimated for each hydrogeologic unit within the Yuma area. Transmissivity, and hydraulic conductivity were estimated for the upper, fine-grained zone (model Layer 3) from multiple-well aquifer pumping tests (ADWR, 1992). Hydraulic conductivity for the river valley floors and Clay B (model Layer 2) was estimated based upon data for the upper, fine-grained zone and assuming a decrease in value of two orders of magnitude. This decrease is presumed to be representative of the relationship of hydraulic conductivity between coarse sand (upper, fine-grained zone) and clayey-silt (river valley floors and Clay B) (Freeze and Cherry, 1979, p.29). Hydraulic conductivity data for the sediments above Clay B beneath the Yuma Mesa (Model Layer 1) were initially assumed to be identical to the upper, fine-grained zone (Model Layer 3). Transmissivity for the lower, coarse-gravel zone was adopted from Olmsted and others (1973).

Quantification and distribution of aquifer storage values were adopted primarily from work previously conducted by Olmsted and others (1973) and Harshbarger and Associates (1971). In general, all layers were modeled as unconfined throughout the Yuma area except for the southern portion of South Gila Valley and where Clay B exists beneath Yuma Mesa. In South Gila Valley a total of 100 feet of clay was identified by Olmsted and others (1973) which acts as a confining layer for the lower coarse gravel zone (model Layer 4). Clay B beneath the Yuma Mesa also acts as a confining layer for the upper, fine-sand and lower coarse gravel zones (model Layers 3 and 4). Specific yield values for all model layers were based upon neutron moisture probe data from Yuma Mesa (Olmsted and others, 1973). Storativity values were based upon a long-term multiple-well aquifer pumping test conducted on Yuma Mesa in 1971 (Harshbarger, 1971).

The initial layer-wide averages of each parameter that were developed and used in the model are provided in Table 13. During calibration aquifer parameters were modified and the calibrated layer-wide average and range are also provided in Table 13.

Vertical Leakance Between Layers

Vertical leakance between layers one and two, two and three, and three and four was modeled using the VCONT option. MODFLOW requires VCONT to be calculated outside of the model then input as an array. The equation used to calculate VCONT is provided below and is used as an example between model Layers 1 and 2:

Where:

$$VCONT_{1-2} = \frac{1}{\frac{(V_1)/2}{Kv_1} + \frac{(V_2)/2}{Kv_2}}$$

$VCONT_{1-2}$ = vertical leakance between layers one and two (1/days)
V_1 = saturated thickness of model layer one (feet)
V_2 = saturated thickness of model layer two (feet)
Kv_1 = vertical hydraulic conductivity of layer one (feet/day)
Kv_2 = vertical hydraulic conductivity of layer two (feet/day)

Table 13
Summary of Aquifer Parameters Model Layer-Wide

	Initial Average	*Calibrated Average*	*Calibrated Range*
Horizontal Hydraulic Conductivity			
Layer 1	540 Ft/Day	540 Ft/Day	420 - 670 Ft/Day
Layer 2	5 Ft/Day	5 Ft/Day	2 - 15 Ft/Day
Layer 3	540 Ft/Day	80 Ft/Day	25 - 134 Ft/Day
Layer 4		Modeled as Transmissivity (4)	
Specific Yield			
Layer 1	32%	32%	30% - 34%
Layer 2	13%	13%	5% - 20%
Layer 3	12%	28%	18% - 30%
Layer 4	0.5%	23%	18% - 30%
Storativity			
Layer 1	N/A	N/A	
Layer 2	0.003	0.003 (1)	
Layer 3	0.003	0.003 (2)	
Layer 4	0.003	0.003 (3)	

Notes:

N/A = not applicable
(1) = beneath Yuma Mesa only
(2) = beneath Clay B only
(3) = beneath Clay B and southern portion of South Gila Valley
(4) = refer to Figure 5 for the calibrated range of values.

During calibration the model was very sensitive to VCONT. This parameter was increased during calibration to achieve better results. Table 14 presents the initial estimates of the ratio of horizontal to vertical hydraulic conductivity (Kh:Kv) and calibrated VCONT. The final ratio Kh:Kv for each model layer could not be mathematically calculated, however it is evident that the calibrated ratios are less than the initial estimates since VCONT had to be increased during calibration.

Table 14
Estimates of the Ratio of Horizontal to Vertical Hydraulic Conductivity Within Each Model Layer and Calibrated VCONT

Model Layer	*Initial Kh:Kv Ratio*	*Calibrated VCONT*
Layer 1	100:1	VCONT Parameter Increased 10x between Layers 1 and 2
Layer 2	1000:1	VCONT Parameter Increased 5x between Layers 2 and 3
Layer 3	100:1	VCONT Parameter Increased 2x between Layers 3 and 4
Layer 4	10:1	

Conductance of the Colorado and Gila Rivers

Conductance of the stream bed is a component of the Streamflow-Routing package developed by Prudic (1989) that permits the modeling of the hydraulic interconnection between the surface water feature and the groundwater system. The conductance value is a product of the stream bed vertical hydraulic conductivity, width and stream length per model cell (i.e., wetted area) divided by the stream bed thickness. Therefore, estimating stream dimensions and vertical hydraulic conductivity are very important.

The cross-sectional dimensions of the Colorado River were obtained from survey data provided by the U.S. Bureau of Reclamation (1991). These survey data illustrate river bottom elevation profiles at approximate 1.5 mile intervals between Laguna and Morelos Dams for the years 1981 and 1986. Initial estimates of vertical hydraulic conductivity data for the Colorado River were obtained from Loeltz and Leake (1983). The calibrated range of vertical hydraulic conductivity for the Colorado River is presented in Table 15.

Table 15
Calibrated Vertical Hydraulic Conductivity Values for Rivers, Canals and Drains Within the Yuma Area
(FEET/DAY)

Surface Water Feature	*Range*	*Average*
Rivers		
Colorado River	0.088 - 0.01	0.039
Gila River	0.04 - 0.01	0.025
Canals		
All-American	2.0 - 1.5	1.8
Gila Gravity Main	0.21 - 0.24	0.21
Yuma Main	0.12	0.12
East Main	0.15	0.15
West Main	0.25 - 0.15	0.21
Central	0.25	0.25
South Gila Main	0.10	0.10
North Gila Main	0.21	0.21
Lateral 242	0.24	0.24
Alamo	0.85	0.85
Alamo del Norte	0.85	0.85
La Principal	0.85 - 0.05	0.15
Drains		
Drain #1	2.0	2.0
Bruce Church	10.0	10.0
Araz	10.0	10.0
Reservation Main	10.0	10.0
DPOC 1, 2, 3 & 4	0.24	0.24
Yuma Valley Main	0.17	0.17
Gardenshire	0.17	0.17
East	0.17	0.17
North	0.17	0.17
South	0.17	0.17
Southeast	0.17	0.17
Southwest	0.17	0.17
Stub No. 2	0.17	0.17

Note: If only single value was provided in Range column, then only this value was simulated.

The dimensions of the Gila River were estimated from U.S. Geological Survey topographic maps. No data regarding river bottom elevations were available, therefore, the river bottom elevation was assumed to be 15 feet below land surface. The calibrated range of vertical hydraulic conductivity for the Gila River is presented in Table 15.

Canals and Drains

As previously discussed, conductance of the canal bottom is a component of the Streamflow-Routing package developed by Prudic (1989) that permits the hydraulic interconnection between the surface water feature with the groundwater system. The conductance value is a product of the canal bottom or lining materials vertical hydraulic conductivity, width and canal length per model cell (wetted area) divided by the canal bottom thickness. Therefore, estimating canal dimensions and vertical hydraulic conductivity are very important.

Construction data for canals located within the U.S.A. were obtained from U.S. Department of Interior, project data report (U.S. Department of Interior, 1981) and are summarized in Table 6. Data for canals constructed in Mexico were estimated based upon a field trip conducted in 1990. Initial estimates of vertical hydraulic conductivity were obtained from various sources. For canals lined with concrete in excellent condition the initial vertical hydraulic conductivity (Kv) was estimated to be 0.05 Ft/Day based upon seepage study conducted on the Tucson Aqueduct portion of the Central Arizona Project (U.S. Bureau of Reclamation, 1989). For canals lined with concrete in fair condition the initial estimate of Kv was determined to be 0.24 Ft/Day (U.S. Geological Survey, 1980). For unlined canals the initial estimate Kv was determined to be 0.85 Ft/Day (U.S. Geological Survey, 1980).

Initial estimates of Kv for the All-American, Gila Gravity Main and Yuma Main canals were calculated using a different methodology. Vertical hydraulic conductivity was estimated using Darcy's Law by dividing the reported leakage rate per mile from Olmsted and others (1973) by the total cross-sectional area of the canal assuming a unit hydraulic gradient of 1:1. However, these initial estimates proved to underestimate the leakage out of the canals and subsequently needed to be increased during calibration.

Construction data for drains were not available and were estimated from field trips and observations. Dimensions of width, depth and Kv were approximated for each drain and are presented in Table 16.

Water Budgets of the Model Area

Steady-State

A groundwater budget was developed for the steady-state calibration of the groundwater flow model. True steady-state conditions existed in the Yuma area prior to the development of irrigated agriculture at the beginning of this century. However, due to historical data limitations and time constraints, the year 1978 was determined to be sufficient for steady-state modeling purposes. This was justified by analyzing Colorado River inflow data and changes in groundwater storage. Surface water inflow was relatively constant between 1975 and 1978 and total flow only varied an average of 5 percent. Changes in groundwater storage were estimated by the U.S. Bureau of Reclamation and were relatively constant during the same three year period since groundwater levels did not change significantly (U.S. Bureau of Reclamation, 1978-1989a). Therefore, 1978 was considered steady-state for modeling purposes.

Various components of groundwater inflow and outflow have been identified and analyzed for steady-state conditions. The inflow components include recharge from agricultural irrigation, seepage from canals, Colorado and Gila River losses, and groundwater underflow below Laguna Dam and at Dome Narrows. The outflow components include groundwater pumpage, aquifer discharge to drains, groundwater return flow to the Colorado River, evapotranspiration from phreatophytes, and underflow west to Mexicali Valley and south along the Southern International Boundary. Data developed for all water budgets were summarized for model simulation years 1978 through 1989. However, data for the steady-state water budget includes only the six month period between April 1978 through September 1978. The conceptual water budget for steady-state conditions is presented in Table 17. The water budget covers only the United States portion of the modeled area, since most data for Mexico were unavailable.

Table 16
Construction Characteristics of Major Drains

Drain	Lining Status	Bottom Width [1] (Feet)	Depth Below Land Surface (Feet)	Total Length [2] (Miles)
North Gila Drain #1	Unlined	5	10	4.3
Bruce Church	Unlined	5	5	1.7
DPOC #1	Lined	5	5	3.1
DPOC #2	Lined	5	5	3.1
DPOC #3	Lined	5	5	1.75
Reservation Main	Unlined	10	10	11.5
Araz	Unlined	5	5	4.1
Yuma Main	Unlined	50	20	20.4
North	Unlined	5	5	3.1
Gardenshire	Unlined	10	10	1.5
East	Unlined	15	10	7.4
Stub No. 2	Unlined	5	5	1.4
Southeast	Unlined	5	5	3.0
Southwest	Unlined	5	5	4.1
South	Unlined	5	5	4.7
Yuma Mesa Outlet [3]	Buried Pipe	Not Modeled		

Notes:

(1) Bottom width and depth estimated from field inspection or best guess.

(2) Length of each drain obtained from U.S.G.S. 7.5 minute topographic quadrangle maps.

(3) Seepage from Yuma Mesa Outlet drain not simulated. However, discharge into the Colorado River from the drain and the Yuma wastewater treatment plant were simulated together.

The water budget indicates approximately seven percent more inflow than outflow within the Yuma area. A portion of this discrepancy may be attributed to not accounting for the estimated decrease of groundwater in storage and the general error in estimating each of these water budget components. The change of groundwater in storage for 1978 was estimated by the U.S.B.R. as a net loss of 26,100 AF (U.S. Bureau of Reclamation, 1978-1989a). A brief discussion of each water budget component is presented after the discussion on transient-state water budgets (Chapters 3 and 4 provide a more detailed discussion).

Table 17
Steady-State Conceptual Groundwater Budget for the United States Portion of the Yuma Area
April - September 1978
(All data rounded to nearest 100 Acre-Feet)

Inflow	
Agricultural Recharge	195,400 AF
Canal Seepage	117,600 AF
River Loss to Aquifer	0 AF
Underflow	1,700 AF
Total	**314,700 AF**
Outflow	
Groundwater Pumpage	108,500 AF
Discharge to Drains	59,000 AF
Return Flow to River	36,500 AF
Evapotranspiration	22,500 AF
Underflow	67,000 AF
Total	**293,500 AF**

Transient-State

Conceptual groundwater budgets were developed for the two periods of transient-state calibration of the groundwater flow model. Each budget corresponds to a phase of the calibration process. Pre-1983 Colorado river flooding conditions were calibrated between October 1978 and March 1983, while flooding and post-flooding conditions were calibrated between April 1983 and March 1989.

Various components of groundwater inflow and outflow have been identified and analyzed for transient-state conditions. In some cases these components are identical to steady-state conditions. The inflow components include recharge from agricultural irrigation, seepage from canals, Colorado and Gila River losses, and groundwater underflow below Laguna Dam and Dome Narrows. The outflow components include groundwater pumpage, aquifer discharge to drains, groundwater return flow to the Colorado River, evapotranspiration from phreatophytes, and underflow exiting west to Mexicali Valley and south across the Southern International Boundary. Estimates developed for all water budgets used monthly annual data and were summarized to correspond to water years. The groundwater budgets for transient conditions are presented in Table 18.

These water budgets indicate that there is 8 percent more groundwater outflow than inflow during the 1978-1983 pre-Colorado River flooding period and 2 percent more outflow during the 1983-1989 flooding and post-Colorado river flooding period. However, this is contrary to the groundwater level rises that occurred beneath the Yuma Mesa and the northern portion of Yuma Valley during the same time period. The change in groundwater storage for the pre-flooding period was estimated by the U.S.B.R. as a net loss of 24,500 AF and for the post-flooding period as a net gain of 43,400 AF. This change of groundwater in storage would indicate that the pre-Colorado River flooding water budget is conceptually correct and the post-Colorado River flooding water budget is not and should reflect more inflow than outflow. This discrepancy for the post-flooding simulation may be attributed to the error in estimating each of these water budget components, specifically the hydraulic interaction between the Colorado River and the groundwater system. As previously mentioned in Chapter 4, the accuracy of the stream gages within the Yuma area may vary within 15 percent of actual streamflow (Table 10). This

Table 18
Transient-State Conceptual Groundwater Budgets for the United States Portion of the Yuma Area
(All data rounded to nearest 100 acre-feet)

	1978-1983 Pre-Flooding [1]	*1983-1989 Post-Flooding* [2]
Inflow		
Agricultural Recharge	262,400 AF/Year	287,700 AF/Year
Canal Seepage	206,200 AF/Year	205,100 AF/Year
River Loss to Aquifer	133,400 AF/Year	174,100 AF/Year
Underflow	3,400 AF/Year	3,400 AF/Year
Total	605,400 AF/Year	670,300 AF/Year
Outflow		
Groundwater Pumpage	278,000 AF/Year	257,500 AF/Year
Discharge to Drains	139,800 AF/Year	159,800 AF/Year
Discharge to River	79,100 AF/Year	86,500 AF/Year
Evapotranspiration	29,100 AF/Year	31,500 AF/Year
Underflow	133,300 AF/Year	150,200 AF/Year
Total	659,300 AF/Year	685,500 AF/Year

Note:

(1) Pre-Flood = October 1978 - March 1983 (4.5 year), values represent 4.5 year average
(2) Post-Flood = April 1983 - March 1989 (6 year), values represent 6 year average

limitation in stream gage accuracy can have a significant impact on estimating the volume of groundwater return flows to the Colorado River when using only stream gaging data.

A brief discussion of each water budget component for steady-state and transient-state water budgets is discussed below. Refer to Chapter 3 for a more detailed discussion of each water budget component.

Recharge

Maximum potential recharge from agricultural irrigation was estimated for each subarea (irrigation district) within the Yuma area. Cropped acreage and water applied to farms for each subarea was provided by the U.S.B.R. Crop Census reports (U.S. Bureau of Reclamation 1978-

1989b). A detailed explanation on how recharge was estimated for each year was previously discussed in Chapter 3. Recharge was distributed to the uppermost active model cell, generally layer two in the river valleys and layer one on Yuma Mesa. Figure 33 delineates which model cells simulate recharge from agricultural irrigation.

Recharge from agricultural irrigation was distributed within the model based upon several factors. These factors include the total estimated maximum potential annual recharge volume for each subarea (irrigation district), the total estimated seasonal irrigated acres per subarea (i.e., summer and winter), and the total estimated seasonal irrigated acres per model cell. The seasonal recharge rate per acre for each subarea was derived by dividing the total estimated annual maximum potential recharge per subarea by the total seasonal irrigated acres within that subarea. The seasonal recharge rate per subarea was then multiplied by the total estimated seasonal irrigated acres per model cell giving rise to the total estimated recharge for that model cell for each season (i.e., winter and summer). The seasonal recharge rate per acre was calculated to be generally higher during the summer season than during the winter season. Table 18 contains the initial estimated annual recharge rate per acre for each subareas within the Yuma area between 1978 and 1988.

The maximum potential recharge for the steady-state simulation was estimated at 195,400 AF. The maximum potential recharge for the transient-state pre-Colorado River flooding period was estimated at 1,180,800 AF and for the post-Colorado River flooding period was estimated at 1,726,200 AF.

Pumpage

Groundwater pumpage from the coarse-gravel zone (model Layer 4) was simulated for both steady-state and transient-state conditions. Total groundwater pumpage per model cell was summarized into a single volumetric pumping rate (FT^3/Day). Annual pumpage data for each well located in either Arizona or California were obtained from the U.S.B.R. Ground Water Status reports (U.S. Bureau of Reclamation, 1978-1989a). These pumpage estimates do not include domestic use since they are not required to report to the U.S.B.R.. Pumpage for domestic use was assumed to be a small portion of the overall groundwater pumpage in the Yuma area and its absence would not have a significant impact on the model results. Refer to Table 8 for annual reported total pumpage for the Yuma area and Mexico.

Annual pumpage data for Mexicali Valley and Mesa Arenosa well field in Sonora, Mexico were provided as total volumes and not from individual wells. The distribution of pumpage within Mexicali Valley was based upon estimating the percentage of wells located within the model domain. Approximately 20 percent of all wells located within the Mexicali Valley were estimated to be located within the model domain using a large scale map provided by the U.S.B.R. Therefore, only 20 percent of the annual pumpage from Mexicali Valley was simulated in the model. The areal distribution of groundwater withdrawals from Mexicali Valley was simulated by attributing pumpage to alternating model cells west of the Colorado River in Mexico. However, since the water budgets were prepared for the United States portion of the model they do not include groundwater pumpage from Mexico.

All pumpage reported from the Mesa Arenosa well field east of San Luis, Sonora was simulated in the model. Distribution of pumpage for the well field was slightly more precise than for Mexicali Valley. Locations of wells were obtained from U.S. Geological Survey topographic maps. Pumpage per well between 1978 and 1986 was based upon individual well pumpage records obtained from the U.S. Geological Survey for 1977, the latest year individual pumpage records were available. Distribution of pumpage per well for 1987-89 was based upon a reconnaissance field trip conducted in 1989 by U.S.B.R. personnel. This field trip identified wells that were currently pumping and those that apparently had not pumped in years. The total annual volume of pumpage reported was then divided evenly between each well that was identified as operational.

Groundwater pumpage within the United States for the steady-state simulation was estimated to be one-half of the total annual reported pumpage for 1978 and equals 108,450 AF representing the six month period between April 1978 through September 1978. Groundwater pumpage within the United States for the transient-state pre-Colorado River flooding period was estimated to be one-half of the annual reported pumpage for 1978 and the total pumpage from 1979 through 1982 and one-half of the annual reported pumpage from 1983. The total United States pumpage during the pre-Colorado River flooding period was estimated to be 1,180,800 AF. Groundwater pumpage within the United States during the post-Colorado River flooding period was estimated to be one-half of the annual reported pumpage for 1983 and the total pumpage from 1984 through 1988 and one-half of the annual reported pumpage for 1989. The pumpage within the United States for post-flooding simulation was estimated to be 1,726,200 AF.

Canal Seepage

Canal seepage losses to the groundwater system were simulated using the Stream Flow Routing Package (Prudic, 1989) and quantified for all the major canals within the United States in the Yuma area. These canals include the All-American, Gila Gravity Main, Yuma Main, North Gila Main, South Gila Main, East and West Main, Central, A and B canals (Figure 24). The U.S.B.R. Crop Census Reports contain monthly canal transportation losses per subarea (irrigation district) (U.S. Bureau of Reclamation, 1978-1989b). However, these transportation losses represent the total losses for the entire subarea and may not be reflective of any one canal. Seepage estimates for the All-American and Gila Gravity Main canals were adopted from Olmsted and others (1973). Annual seepage rates per lineal length of the All-American canal was reported to be 4300 AF/Mile/Year and for the Gila Gravity Main canal 2000 AF/Mile/Year. The maximum seepage rate for the Yuma Main canal was estimated by comparing gaging data at the canal inflow and outflow locations. The maximum annual seepage rate per lineal length of canal was calculated to be 2800 AF/Mile/Year for 1978 presuming the canal is 3.3 miles long. Table 7 presents the initial estimated seepage rate per mile per year.

The total canal seepage losses from all canals within the United States was estimated for steady-state simulation at 117,600 AF. The total seepage losses for transient-state pre-1983 Colorado River flooding was estimated at 927,900 AF and for post-flooding at 1,230,500 AF.

Groundwater/Colorado River Interaction

Surface water interaction with the groundwater system was simulated using the Streamflow Routing Package developed by Prudic (1989). Quantification of groundwater return flow to the Colorado River and river losses to the aquifer were estimated using gaging data between Laguna Dam and Morelos Dam from rivers, drains and canal wasteways. However, groundwater return flow to the Gila River could not be accurately quantified since only one stream gage exists in the Yuma area.

The Colorado river was divided into three segments to quantify the surface water - groundwater interrelationship; Laguna Dam to Yuma Gage, Yuma Gage to Morelos Dam and Morelos Dam to the Southern International Boundary (Figure 26). All gaged inflows into the river were summarized for each of these segments and outflows were subtracted from inflows to derive the volume of water the river was gaining or losing to the groundwater system.

Estimates of groundwater return flow or river losses to the groundwater system using gaging data for steady-state were compared to modeling efforts conducted by Loeltz and Leake (1983). They developed a series of two-dimensional cross-sectional models between Laguna Dam and Morelos Dam to estimate groundwater return flows to the Colorado River between 1973 and 1978. The estimates of groundwater return flow using gaging data for 1978 are very similar to the Loeltz and Leake (1983) modeling results. Groundwater return flow estimates between Laguna Dam and Morelos Dam were calculated to be 36,500 AF between April and September 1978. Loeltz and Leake (1983) estimated groundwater return flows to be 39,500 AF for the same time period. The Colorado River did not flow downstream of Morelos Dam in 1978, therefore, there was no surface water loss to the groundwater system for this segment of the Colorado River.

Estimates of groundwater return flow or river losses to the groundwater system using gaging data for the pre-Colorado River transient-state period, in general, indicate that the river is a natural drain to the groundwater system between Laguna Dam and Morelos Dam, and the river loses water to the groundwater system downstream of Morelos Dam. Gaging data between 1978 and 1983 indicate that the Colorado River was primarily gaining from the groundwater system between Laguna Dam and Morelos Dam and losing water to the groundwater system between Morelos Dam and the Southern International Boundary. Groundwater return flows for the pre-flooding period were estimated to be 356,000 AF and river losses to the groundwater system were estimated at 600,200 AF between Laguna Dam and Morelos Dam.

Estimates of Colorado River losses to the groundwater system using gaging data for the post-Colorado River flooding transient-state simulation did not agree with the conceptual surface water - groundwater system interrelationship. Gaging data between 1984 and 1989 indicate that the Colorado River was gaining water from the groundwater system downstream of Morelos Dam. Actual hydrogeologic conditions indicate that the river bottom elevation is consistently above the groundwater elevation dictating the river should always be losing water to the groundwater system. This error in the gaging data may be attributed to the accuracy of the stream gages. As previously mentioned, some stream gages in the Yuma area may be only accurate within 15 percent of the total amount of water flowing past the gage (Curt Webb, U.S. Geological Survey, Personal Communication). Therefore, groundwater return flows estimated using gaging data between Morelos Dam and the Southern International Boundary were not accounted for in the water budget.

The water budget for the post-Colorado River flooding transient-state period accounts for groundwater return flows between Laguna Dam and Morelos Dam estimated at 518,900 AF. River losses to the groundwater system during and after the Colorado River flooding were estimated at 1,044,500 AF between Laguna Dam and the Southern International Boundary.

Aquifer Discharge to Drains

Groundwater discharge to major drains was simulated using the Streamflow Routing Package (Prudic, 1989) and was quantified within the Yuma area. These drains include the Yuma Valley main and tributary drains, Yuma Mesa Outlet, Reservation Main, Araz, North Gila Main, Bruce Church, and the Drainage Pump Outlet Channel (DPOC) drains located within South Gila Valley (Figure 25). However, discharge to the Yuma Mesa Outlet and DPOC drains is from groundwater pumpage and not natural aquifer discharge, therefore, flows from these drains were simulated by groundwater pumpage. Discharge data were obtained from several sources including calendar year data from U.S.B.R. Ground Water Status reports (U.S. Bureau of Reclamation, 1978-1989a) and monthly data from the International Boundary and Water Commission Western Water Bulletins (I.B.W.C., 1977-1989).

Steady-state and transient-state water budgets incorporate reported discharge from the drains within the Yuma area. The total aquifer discharge to drains for the steady-state simulation was estimated at 117,600 AF. The total aquifer discharge to drains for transient-state pre-

Colorado river flooding simulation was estimated at 629,000 AF and for post-flooding simulation at 958,700 AF.

Evapotranspiration Data

Groundwater withdrawal from native floodplain vegetation along the Colorado River was simulated using the ET module of MODFLOW. The phreatophyte vegetation type was identified by Younker and Anderson (1986) to be predominately salt ceder, cottonwood and willow, screwbean and honey mesquite, arrow weed and creosote. The maximum potential consumptive use from all phreatophytes was simulated using the consumptive use rate of salt cedar and cottonwood-willow assemblage. Consumptive use from salt ceder and cottonwood-willow was used since they consume the most groundwater of any of the phreatophytes in the Yuma area. The consumptive use rates were estimated by Raymond and Rezin (1989) to be 3.9 AF/Ac/Yr north of Yuma in Parker Valley and 6-7 AF/Ac/Yr near Phoenix by Gay and Hartman (1982).

Evapotranspiration (ET) from phreatophytes was simulated within each model cell that contained either the Colorado and Gila Rivers or the Island area between the Southern International Boundary and Laguna Dam. The Island area is the undeveloped region south of the Bard I.D. and north of the Colorado River (Figure 3). The initial ET rate was 4.0 AF/Ac/Yr for all cells that contained the rivers and 2.0 AF/Ac/Yr for the Island area. The decreased ET rate within the Island area was reflective that other phreatophytes besides salt-cedar or cottonwood-willow assemblage existed in the area.

The extinction depth criterion within the ET package dictates at what depth to water the phreatophytes cease to withdraw groundwater. Graf (1980) states that the single most important controlling factor in phreatophyte growth is the depth to water less than 20 to 30 feet below land surface. Therefore, the extinction depth simulated in the model was estimated to be 20 feet. Phreatophytes were simulated to withdraw groundwater from the upper, fine-grained aquifer (i.e., model Layer 3).

Younker and Anderson (1986) estimated there were approximately 7,500 acres of phreatophytes between the Southern International Boundary and Laguna Dam along the Colorado River in 1981. Estimates of 1981 phreatophyte acreage was assumed to be representative of

1978 conditions. The maximum potential groundwater consumption from phreatophytes for steady-state was estimated at 45,000 AF/Year which was derived by multiplying the estimated acres by the maximum consumptive use (i.e., 7500 Acres * 6 AF/Ac/Year) assuming 100 percent coverage of salt cedar and cottonwood-willow assemblage. This higher consumptive use figure was used for two reasons. First, phreatophyte growth along the river valleys was probably dense without any recent flooding along the Colorado River prior to 1978, and second, the 1981 acreage might not be representative of 1978 conditions and underestimate total acreage.

Younker and Anderson (1986) estimated that there were 8,400 acres of phreatophytes between the Southern International Boundary and Laguna Dam along the Colorado River in 1986. Conditions in 1986 were assumed to be representative for transient-state simulations between 1979 and 1989. The potential groundwater consumption from phreatophytes for transient-state simulations was estimated at 33,000 AF/Year which was derived by multiplying the estimated acres by the lower consumptive use value (8,400 acres * 3.9 AF/Ac/Yr) assuming 100 percent coverage of salt cedar and cottonwood-willow assemblage. The lower consumptive use value was used for transient-state simulations since flooding along the Colorado River probably removed some of the density of phreatophyte growth and the plant type was probably not covered with 100 percent salt cedar and cottonwood-willow assemblage.

Underflow

Groundwater underflow into the Yuma area was estimated by Olmsted and others (1973) at 700 AF/Year and 1000 AF/Year for Laguna Dam and Dome Narrows, respectively. Groundwater exits the United States to the west into Mexicali Valley and the south along the Southern International Boundary. Underflow was estimated using flow nets and water level elevation maps produced by the U.S.B.R. and geologic data obtained from drill logs, aquifer hydraulic conductivity and transmissivity estimates. Underflow into Mexicali Valley from Yuma Valley for the steady-state simulation was estimated at approximately 37,000 AF/Year, while underflow into Mexico along the Southern International Boundary was estimated to be approximately 95,000 AF/Year for 1978. The underflow estimate along the Southern International Boundary includes flow from Fortuna Basin towards the Altar Desert east of the

Boundary Hills. These underflow estimates were also assumed to be representative of the transient-state pre-Colorado River flooding period (i.e., 1978 through 1983).

Underflow into Mexicali Valley was estimated at 41,000 AF and south across the Southern International Boundary at 109,000 AF/Year for 1983. Groundwater underflow estimates for 1989 were identical to 1983, therefore, 1983 values were assumed to be representative for the transient-state post-Colorado River flooding period (i.e., 1983 through 1989).

CHAPTER VI. MODEL CALIBRATION

Calibration Process

Several criteria were used to evaluate the success of the model calibration. These included comparing model-simulated final water levels to initial water levels, comparing time varying model-simulated water level data with actual well hydrographs and comparing model-generated volumetric water budgets with conceptual water budgets, and comparing output from the streamflow-routing package to stream gaging data and conceptual estimates of canal seepage, aquifer discharge to drains and Colorado and Gila River interaction with the groundwater system.

The calibration process involved identifying areas within the model that did not adequately simulate observed field conditions and then modifying the model input data. Input data were modified to achieve a better match between the model calibrated results and observed field conditions. Data were modified in preferential order based upon the level of confidence of the original estimates. In general, estimates of vertical hydraulic conductivity were considered to be of least confidence and water level data were considered to be of most confidence. Refer to Table 19 for a qualitative ranking of confidence for all the model input data.

Special attention was given to calibrating the model in the northern portion of the Yuma Valley near the Hacienda Estates subdivision (Figure 2). This subdivision is located along the Yuma Mesa/ Yuma Valley escarpment adjacent to the East Main Canal in the northern portion of the Yuma Valley. Historically, this area has had shallow water level problems and one of the objectives of this investigation was to develop a groundwater flow model that would assist Yuma County in evaluating solutions to these shallow water level problems.

Steady-State

The model was initially calibrated to steady-state groundwater flow conditions using water level and hydrologic data for Summer 1978 (i.e., April to September 1978). The Yuma area was assumed to be in steady-state in 1978 for modeling purposes since there were no major

Table 19
Qualitative Level of Confidence Ranking of the Original Yuma Area Model Input Data

Model Input Data	
Vertical Hydraulic Conductivity	Least Confident
Conductance of Rivers, Canals, Drains	↓
Evapotranspiration Estimates	↓
Agricultural Recharge Estimates	↓
Boundary Fluxes	↓
Storage Components	↓
Horizontal Hydraulic Conductivity	↓
Surface Water Flow Gaging Data	↓
Hydrogeologic Contacts	↓
Areal Distribution of Pumpage	↓
Water Level Elevation Data	Most Confident

changes in surface water inflow or outflow or in the volume of groundwater in storage. Steady-state model runs were conducted to refine the areal distribution of hydraulic conductivity and provide initial water levels for the transient simulation which permitted the hydraulic properties and fluxes to be internally consistent (Reilly and others, 1984). The same initial water levels (heads) were assigned to all model layers since there is little vertical head gradient between the upper, fine-grained and the underlying coarse-gravel aquifers. Water level data for each aquifer within the entire Yuma area is not available, therefore, the starting water levels were adopted from U.S.B.R. maps that represent water level elevations from the upper, fine-grained aquifer (i.e., model layer 3). Figure 14 presents the starting measured water levels for March, 1978.

Summary

The model simulated overall groundwater flow directions and elevations very well. However, the model simulated water levels two to five feet higher than measured water levels in Yuma Valley and Reservation-Bard subarea and simulated water levels 10 feet higher on the Yuma Mesa than measured water levels. The model simulated water levels above measured water levels by one to six feet in the area of Hacienda Estates in the northern portion of Yuma Valley.

The model-generated volumetric water budget provides an independent check of the overall acceptability of the model solution (McDonald and Harbaugh, 1988). If the steady-state model solution is valid, then total inflows should equal total outflows. In the case of steady-state simulations where the change in storage is zero, then the volumetric water budget components of total inflows minus outflows should also approach zero. The final volumetric water budget is presented in Table 20. Total model inflow minus outflow from the calibrated steady-state model simulation is 400 AF, which equals approximately 0.1 percent of the total inflow budget. This is one indication that the model simulates steady-state conditions reasonably well.

Table 20
Final Volumetric Water Budget for Steady-State
(Values rounded to nearest 100 Acre-Feet)

Inflow		*Outflow*	
Storage	0 AF	Storage	0 AF
Constant Head	5,700 AF	Constant Head	38,800 AF
Underflow	1,700 AF	Pumpage	214,100 AF
Recharge	225,200 AF	Evapotranspiration	11,000 AF
Stream Leakage	128,700 AF	Stream Leakage	97,000 AF
Total	361,300 AF	**Total**	360,900 AF

The constant head component of inflow shown in Table 20 indicates that there is underflow into the model domain from the western model boundary of 5,700 AF. This underflow into the model from the west may not actually exist, however, it is difficult to quantify since there are few water level data available from Mexico. This simulated underflow into the model probably can be attributed to estimating constant head water level elevations too high which then created underflow into the western portion of the model domain.

Another criteria for evaluating the steady-state calibration was the output of the streamflow-routing package (i.e., flows in rivers, canals and drains, canal seepage, drain discharge, and groundwater return flows to the rivers). Table 21 presents the comparison of measured stream flow with model-simulated stream flow for selected gaging stations. The model-simulated stream flow compares very well to the stream gaging data.

Canal seepage simulated in the model is an accumulation from all the canals within the modeled area. These canals include: All-American, Gila Gravity Main, Yuma Main, North Gila Main, South Gila Main, East and West Main, Central, A and B canals, and the Mexican canals La Principal, Alamo, and Alamo del Norte (Figure 24). The total simulated seepage from canals located only within the United States was approximately 83,800 AF. The simulated canal seepage compares reasonably well to the conceptual estimates of 117,600 AF (i.e., an under simulation of 29 percent). This difference was considered a reasonable match due to the uncertainty of estimating the volume of seepage from canals, especially the All-American canal.

Aquifer discharge to drains is another feature of the streamflow-routing package that was evaluated. The drains include: Reservation Main, Araz, North Gila Main No. 1, Bruce Church, and the extensive network within the Yuma Valley (Figure 25). The DPOC drains within the South Gila Valley and the Yuma Mesa Outlet drain are simulated using the well package of MODFLOW since they obtain all of their water from drainage wells. Water from all drains, except Yuma Valley, was added to the Colorado or Gila Rivers using the streamflow-routing package. The total simulated aquifer discharge to drains was approximately 47,000 AF. The simulated aquifer discharge to drains compares reasonably well to the conceptual estimates of 59,000 AF (i.e., an under simulation of 20 percent). This difference was considered a reasonable match, however the model significantly under-simulated aquifer discharge to the Reservation Main and Araz drains.

The interaction of the rivers with the groundwater system is another important component of the streamflow-routing package. The model simulated groundwater return flow to the

Table 21
Comparison of Conceptual and Model-Simulated Stream Flow for Selected Stream Gages, Steady-State
April - September, 1978
(Values rounded to nearest 100 Acre-Feet)

Stream Gage Locations	*Stream Gage*[1]	*Conceptual*	*Model-simulated*	*Percent Difference*
Colorado River @ Laguna Dam	09429600	183,400 AF	183,400 AF	0%
Colorado River @ Yuma Gage	09521100	301,500 AF	279,900 AF	-7%
Colorado River @ Morelos Dam	09522030	842,400 AF	825,400 AF	-2%
Colorado River @ S.I.B.	09522200	0 AF	11,900 AF	100%
Gila River @ Dome Narrows	09520500	40 AF	40 AF	0%
All-American Canal below Imperial Dam	09523000	2,646,900 AF	2,648,100 AF	0%
All-American Canal below Pilot Knob Wasteway	09527500	2,139,000 AF	1,877,100 AF	-12%
Yuma Main Canal diversion from All-American canal	09524000	249,200 AF	249,300 AF	0%
Yuma Main Canal below Colorado River Siphon	09525500	193,200 AF	197,300 AF	2%
Gila Gravity Main Canal @ Imperial Dam	09522500	222,400 AF	222,500 AF	0%
Gila Gravity Main Canal @ Yuma Mesa Pumping Plant	09522900	166,100 AF	165,900 AF	0%

NOTE: (1) Refer to Figure 26 for location of stream gages

Colorado and Gila Rivers at 36,300 AF between Laguna Dam and Morelos Dam. The model did not simulate any river losses to the groundwater system, since the river did not flow downstream of Morelos Dam in 1978. The simulated groundwater return flow compares very well to the conceptual estimates of 36,500 AF (i.e., an under simulation of one percent). However, the model did simulate a minor amount of groundwater return flow to the Colorado River downstream of Morelos Dam. This is contrary to the conceptual estimates and was attributed to the initial river bottom elevations being below the water table. This problem was subsequently modified during the transient-state calibration.

Transient-State

The model simulates transient-state surface water and groundwater conditions between October, 1978 and March, 1989. The transient-state modeling process was divided into two calibration periods: pre-Colorado River flooding (i.e., October 1978 through March 1983) and post-Colorado River flooding (i.e., April 1983 through March 1989). Steady-state model-simulated final heads were used as initial heads for the pre-Colorado River flooding (pre-flooding) calibration period. The pre-flooding calibration used measured water level data from March, 1983 as target final heads. Pre-flooding calibration final heads were then used as initial heads for the post-Colorado River flooding (i.e., flooding and post-flooding) calibration and measured water levels from March, 1989 were used as target final heads. Figures 31 and 32 illustrate the measured water levels for March, 1983 and March, 1989, respectively.

Summary: 1978-1983, Pre-Colorado River Flooding

The transient-state model generally simulates groundwater flow directions and water level elevations very well for the pre-flooding calibration period. However, the model simulated water levels approximately three feet higher than measured water levels in the northern Yuma Valley, five feet to ten feet higher than measured water levels on Yuma Mesa and two feet to five feet lower than measured water levels adjacent to the All-American canal in the Reservation Subarea. These simulated final water levels were then used as initial heads for the post-Colorado River flooding calibration period. Figure 34 presents the pre-flooding final calibrated heads versus the measured water levels from March, 1983.

Comparing actual well hydrographs to model-simulated water levels was another criteria used to evaluate the success of the model calibration. The selected wells used are located primarily within Yuma Valley and Yuma Mesa (Figure 12). Appendix III contains hydrographs of measured and model-simulated water levels superimposed for easy comparison. The model simulated water levels within the northern portion of Yuma Valley near the Hacienda Estates subdivision very well as indicated by the well hydrographs. The model simulated water levels within one to five feet of measured water levels in the Yuma Valley. However, the model simulated water levels wihin one to 15 feet of measured water levels on Yuma Mesa.

The model-generated volumetric water budget provides an independent check of the overall acceptability of the model solution (McDonald and Harbaugh, 1988). The final model-generated volumetric water budget for the pre-flooding calibration is presented in Table 22. This volumetric water budget agrees reasonable well with the conceptual water budget developed for the United States portion of the modeled area. The volumetric water budget indicates that there is a model-wide net decrease in the volume of groundwater in storage of 161,100 AF/Year. This figure is contrary to the U.S.B.R. estimated change of groundwater in storage since their calculation only accounts for the agricultural regions of the Yuma area and does not account for the Fortuna Basin and other outlying regions including Mexico. This model-wide simulated decrease of groundwater in storage can be attributed to water level declines between 1978 and 1983 of 5 feet and 10 feet within the area between the groundwater mound beneath the Yuma Mesa and the Mesa Arenosa well field in Mexico.

Another contributing factor to the model simulating a large decrease of groundwater in storage may be due to the error in the steady-state model calibration. The initial water levels for this calibration period were adopted from the end of the steady-state calibration. As previously stated, the steady-state calibration overestimated water level elevations for the groundwater mound beneath the Yuma Mesa including south into Mexico. The combination of the overestimated initial heads and the decline in measured water levels in the same region may have contributed to the very large decrease of groundwater in storage simulated during the pre-flooding calibration period.

Table 22
Final Volumetric Water Budgets for Transient-State
Pre and Post Colorado River Flooding Calibration Periods
Acre-Feet/Year
(All values rounded to nearest 100 AF)

Inflow	*Pre-Colorado River Flooding (1)*	*Post-Colorado River Flooding (2)*
Constant Head	13,700	8,800
Underflow	3,400	3,400
Ag. Recharge	319,600	339,100
Stream Leakage	225,700	287,100
Total	562,400	638,400
Outflow		
Underflow	69,200	100,600
Pumpage	438,600	406,600
Evapotranspiration	25,700	29,000
Stream Leakage	190,000	155,800
Total	723,500	692,000
Inflow-Outflow	–161,100 AF/Year	–53,600 AF/Year

Notes:
1. Pre-Colorado Flooding: October 1978 - March 1983
2. Colorado Flooding and Post-Flooding: April 1983 - March 1989

The constant head component of inflow shown in Table 22 indicates that there is underflow into the model domain from the western model boundary of 13,700 AF/Year (similar to the steady-state calibration). This underflow from the west may not exist, however, it is difficult to quantify since there are few water level data available from Mexico. The simulated underflow probably can be attributed to either the constant heads being estimated at too high an elevation or an overestimate of groundwater pumpage for Mexico. Both of these conditions would simulate water level elevations too low adjacent to the model boundary creating a minor component of underflow into the western portion of the model domain.

Output from the streamflow-routing package for the pre-flooding calibration were compared to conceptual estimates to evaluate the success of the calibration. Output from the streamflow-routing package included flows in rivers, canals and drains, seepage from all canals, aquifer discharge to all drains and groundwater return flow to the river and river losses to the groundwater system. Table 23 presents the comparison of measured stream flow with model simulated stream flow for selected gaging stations. The model simulated stream flow compares very well to the stream gaging data.

The total simulated seepage from canals located within the United States was approximately 146,300 AF/Year between 1978 and 1983. The simulated canal seepage compares fairly well to the conceptual estimates of 206,200 AF/Year (i.e., an under simulation of 29 percent). This difference was considered a reasonable match due to the uncertainty of estimating the conceptual volume of seepage from canals, especially the All-American canal.

Aquifer discharge to drains is another feature of the streamflow-routing package that was compared to conceptual estimates. The total simulated aquifer discharge to drains was approximately 115,500 AF/year. The simulated aquifer discharge to drains compares reasonably well with the conceptual estimates of 139,800 AF/Year (i.e., an under simulation of 17 percent). This difference was considered a reasonable match, however, the model significantly under simulated aquifer discharge to the North Gila and Araz drains.

The interaction of the rivers with the groundwater system is another important component of the streamflow-routing package. The model simulated groundwater return flows to the Colorado and Gila Rivers at 57,200 AF/Year between Laguna Dam and Morelos Dam, while simulating river losses to the groundwater system at 19,500 AF/Year downstream of Morelos Dam. The simulated groundwater return flow compares fairly well to the conceptual estimates of 79,100 AF/Year (i.e., an under simulation of 28 percent), however, simulated river losses to the groundwater system is significantly less than the conceptual estimates of 133,400 AF/Year (i.e., an under simulation of 85 percent). Although these numbers are different, this simulation was considered a reasonable match for three reasons. First, as previously discussed in Chapter 3, there is a 5 percent to 15 percent error in the accuracy of the stream gaging data which creates uncertainty in the development of conceptual estimates of groundwater return flow and river losses. Second, the total flows simulated in the Colorado River at Yuma Gage, Northern International Boundary and the Southern International boundary are within 4 percent of the

Table 23
Comparison of Conceptual and Model-Simulated Stream Flow for Selected Stream Gages, Transient-State
October, 1978 - March, 1989
(Values rounded to nearest 100 Acre-Feet)

Stream Gage Locations	*Stream Gage* [1]	*1978-1983 Pre-Flooding* [2]		*Percent Difference*	*1983-1989 Flooding and Post-Flooding* [3]		*Percent Difference*
		Conceptual	Simulated		Conceptual	Simulated	
Colorado River @ Laguna Dam	09429600	2,449,900	2,449,900	0%	32,446,900	32,487,600	0%
Colorado River @ Yuma Gage	09521100	6,500,700	6,657,100	2%	35,957,300	35,627,600	-1%
Colorado River @ Morelos Dam	09522030	8,645,500	8,717,000	1%	14,452,400	14,649,800	1%
Colorado River @ S.I.B.	09522200	5,788,500	6,077,300	5%	43,739,000	42,818,600	-2%
Gila River @ Dome Narrows	09520500	3,339,500	3,337400	0%	1,990,700	1,991,100	0%
All-American Canal below Imperial Dam	09523000	24,347,400	24,339,700	0%	43,709,700	43,731,000	0%
All-American Canal below Pilot Knob Wasteway	09527500	14,026,500	14,618,900	4%	18,497,900	19,366,200	4%
Yuma Main Canal diversion from All-American canal	09524000	1,664,100	1,663,900	0%	2,455,400	2,455,700	0%
Yuma Main Canal below Colorado River Siphon	09525500	1,312,500	1,329,900	1%	1,794,500	1,817,600	1%
Gila Gravity Main Canal @ Imperial Dam	09522500	3,213,600	3,213,600	0%	4,810,400	4,810,400	0%
Gila Gravity Main Canal @ Yuma Mesa Pumping Plant	09522900	1,053,200	1,052,900	0%	1,502,900	1,502,500	0%

Note: (1) Refer to Figure 26 for location of stream gages
(2) 1978-1983 Pre-Flooding: October, 1978 - March, 1983 (4.5 years)
(3) 1983-1989 Flooding and Post-Flooding: April, 1983 - March 1989 (6 years)

measured gaged flows. Even though simulated groundwater return flows and river losses were not close to the conceptual estimates, the total flows in the river were very similar. Third, the model simulates groundwater return flow and river losses where they are conceptually thought to occur within the Yuma area (i.e., return flows are simulated between Laguna Dam and Morelos Dam and river losses are simulated downstream of Morelos Dam).

Groundwater withdrawal from the evapotranspiration (ET) of phreatophytes was also compared to conceptual estimates to evaluate the success of the transient-state simulation. The model simulated groundwater withdrawal from ET at 25,700 AF/Year. The simulated groundwater withdrawal from ET compares very well with the conceptual estimates of 29,100 AF/Year (i.e., an under-simulation of 12 percent).

Groundwater underflow out of the United States into Mexico was estimated to the west into Mexicali Valley and south across the Southern International Boundary. The total volume of groundwater leaving the United States was estimated by flow-net analysis at 133,300 AF/Year. The model simulated groundwater underflow out of the model boundaries at 69,200 AF/Year. This simulated volume is considerably less than the estimated underflow into Mexico from the United States. This difference may be attributed to groundwater pumpage from Mexicali Valley and the Mesa Arenosa well field which are located between the International Border and the model boundaries.

Summary: 1983-1989, Colorado River Flooding and Post-Flooding

The transient-state model generally simulates groundwater flow directions and water level elevations very well for the post-flooding calibration period. However, the model simulates water level elevations approximately two feet to five feet lower than measured water levels in the Reservation-Bard subarea and South Gila Valley, five feet to ten feet higher than measured water levels for the groundwater mound beneath the Yuma Mesa and two feet to five feet higher than measured water levels south of the mound into Mexico. Figure 35 presents the post-flooding final calibrated heads versus the measured water levels from March, 1989.

Appendix III contains measured well hydrographs and model-simulated water levels superimposed together for easy comparison. The model simulated water levels within the northern portion of Yuma Valley near the Hacienda Estates subdivision very well as indicated by well hydrographs. The model simulated water levels approximately one to three feet higher than measured water levels in the area near Hacienda Estates. However, the model simulated water levels within one to 15 feet of measured water levels on Yuma Mesa as indicated by the well hydrographs.

The final model-generated volumetric water budget is presented in Table 22. This volumetric water budget agrees reasonable well with the conceptual water budget developed for the United States portion of the modeled area. The volumetric water budget indicates that there is a model-wide net decrease in the volume of groundwater in storage of 53,600 AF\Year. This figure is contrary to the U.S.B.R. estimated increase of groundwater in storage for the Yuma area since their calculation only accounts for the agricultural regions of the Yuma area and does not account for the Fortuna Basin and other outlying regions including Mexico. This discrepancy can be explained by two reasons. First, the transient-state post-flooding calibration under-simulated water levels (as compared to measured water levels) in the Reservation-Bard subarea, South Gila Valley, east of the groundwater mound beneath the Yuma Mesa and in Mexico adjacent to the western model boundary. This decrease in water level elevations would cause a decrease of groundwater in storage. Second, the error introduced from the pre-flooding transient-state ending heads may have contributed to the model-wide decrease of groundwater in storage. The starting heads for the post-flooding simulation were adopted from the ending heads of the pre-flooding calibration period. As previously mentioned, the pre-flooding calibration overestimated the water levels for the groundwater mound and south to Mexico by approximately five feet, thereby introducing error into the post-flooding calibration starting heads. The combination of the starting heads estimated at too high an elevation and the under-simulation of water levels may have attributed to the model-wide volumetric water budget simulating a net decrease in the volume of groundwater in storage.

The constant head component of inflow shown in Table 22 indicates that there is underflow into the model domain from the western model boundary of 8,800 AF/Year (similar to all previous calibrations). This underflow from the west may not exist, however, it is difficult to quantify since there are few water level data from Mexico. The simulated underflow probably can be attributed to either the constant heads being estimated at too high an elevation or groundwater pumpage for Mexico estimated too high. Both of these conditions would simulate water level elevations too low adjacent to the model boundary creating a minor component of underflow into the western portion of the model domain.

Output from the streamflow-routing package for the post-flooding calibration compared to conceptual estimates was also used to evaluate the success of the calibration. Output from the streamflow-routing package included flow in rivers, canals and drains, seepage from all canals, aquifer discharge to all drains and groundwater return flow to the river and river losses to the groundwater system. Table 23 presents the comparison of measured stream flow with model-simulated stream flow for selected stream gages. The model simulated stream flow compares very well to the stream gaging data.

The total simulated seepage from canals located only within the United States was approximately 155,200 AF/Year. The simulated canal seepage compares fairly well to the conceptual estimates of 205,100 AF/Year (i.e., an under simulation of 24 percent). This difference was considered a reasonable match due to the uncertainty of estimating the conceptual volume of seepage from canals, especially the All-American canal.

Aquifer discharge to drains is another feature of the streamflow-routing package that was compared to conceptual estimates. The total simulated aquifer discharge to drains was approximately 106,200 AF/Year. The simulated discharge to drains compares fairly well to the conceptual estimates of 159,800 AF/Year (i.e., an under simulation of 34 percent). This difference can be attributed to the under simulation of aquifer discharge to the Reservation Main and Araz drains.

The interaction of the rivers with the groundwater system is another important component of the streamflow-routing package. The model simulated groundwater return flows to the Colorado and Gila Rivers at 22,800 AF/Year between Laguna Dam and Morelos Dam, while river losses to the groundwater system were simulated at 48,100 AF/Year downstream of Morelos Dam. Both groundwater return flows and river losses are significantly under simulated as compared to the conceptual estimates of 86,500 AF/Year and 174,100 AF/Year, respectively. Although this simulation under estimates groundwater return flow at 74 percent and river losses at 72 percent, the simulation was still considered reasonable. As previously discussed, this discrepancy can be explained for three reasons. First, there is a 5 percent to 15 percent error in the accuracy of the stream gaging data which creates uncertainty in the development of conceptual estimates. Second, the flow in the Colorado River at Yuma Gage, Northern International Boundary and Southern International Boundary are within 2 percent of the measured gaged flows. Even though simulated groundwater return flows and river losses were not close to the conceptual estimates, the total flows in the river were very similar. Third, the model simulates groundwater return flow and river losses where they are conceptually thought to occur within the Yuma area (i.e., return flows are simulated between Laguna Dam and Morelos Dam and river losses are simulated downstream of Morelos Dam).

Groundwater withdrawal from the evapotranspiration (ET) of phreatophytes was also compared to conceptual estimates to evaluate the success of the transient-state simulation. The model simulated groundwater withdrawal from ET at 29,000 AF/Year. The simulated groundwater withdrawal from ET compares very well with the conceptual estimate of 31,500 AF/Year (i.e., an under simulation of 8 percent).

Groundwater underflow from the United States into Mexico was estimated to the west into Mexicali Valley and south across the Southern International Boundary. The total volume of groundwater leaving the United States was estimated using flow-net analysis at 150,200 AF/Year. The model simulated groundwater underflow out of the boundaries at 100,600 AF/Year. This simulated volume is considerably less than the estimated underflow into Mexico from the United States. This difference may be attributed to groundwater pumpage in Mexicali Valley and the Mesa Arenosa well field which are located between the International Border and model boundaries.

Calibration Summary

The model was calibrated for both steady-state and transient-state groundwater and surface water flow conditions. The calibration process consisted of identifying "poor calibration areas" and modifying the original input data. To evaluate the success of the model calibration the measured final water levels were compared to the simulated final water levels, hydrographs of measured water level data for selected wells were compared to time varying model simulated water level data, model-generated volumetric water budgets were compared to conceptual estimates, and output from the streamflow-routing package were compared to conceptual estimates of stream flow, canal seepage, aquifer discharge to drains, groundwater return flow to the Colorado River and river losses to the groundwater system.

Special attention was given to calibrating the model in the northern portion of Yuma Valley near the Hacienda Estates subdivision. Historically this area has had shallow water level problems and one of the objectives of this investigation was to develop a groundwater flow model to assist Yuma County in evaluating solutions to these problems.

Comparing water levels to evaluate the success of the model simulation was based upon using both model-wide water levels for each layer and water levels within selected zones for specific layers. Three zones were identified in different locations within the model domain which reflect areas that are important hydrologically and are modeled with a relatively high degree of certainty concerning the original input data (Figure 36). Water level data from these three zones were used to evaluate the success of both the model calibration and model sensitivity. Zone 1 is located in the south-western portion of Yuma Valley and straddles the Colorado River between Morelos Dam and the Southern International Boundary, Zone 2 is located in the north-eastern portion of Yuma Valley and encompasses the area around the Hacienda Estates subdivision and Zone 3 is located in the western part of Yuma Mesa (Figure 36).

Calibration of the steady-state model for the Summer of 1978 permitted the refinement of the areal distribution of hydraulic conductivity. The steady-state calibration simulated the model-wide regional groundwater flow system reasonably well in model layers 3 and 4 (i.e., within an average of 6 feet compared to measured water levels) and fairly well in model layers 1 and 2 (i.e., within an average of 18 feet and 8 feet, respectively, compared to measured water levels). Table 24 presents a statistical analysis of the model-wide absolute difference between the final calibrated heads and the measured water levels from March 1978 for each layer.

The model simulates water levels more accurately in certain locations which is illustrated by comparing simulated water levels within each of the three selected zones to measured water levels. The model over simulated water levels by an average of five feet above measured water levels in the south-western part of Yuma Valley (i.e., Zone 1). The model over simulated water levels an average of one to six feet above measured water levels in the north-eastern part of

Table 24
Statistical Analysis of Model-Wide Water Level Difference
Steady-state and Transient-State Calibration

Absolute (ABS) Difference of (Calibrated Water Levels
Minus the Measured Final Water Levels)

Model Layer	*Mean ABS Difference (feet)*	*Median of ABS Difference (feet)*	*Standard Deviation of ABS Difference (feet)*
Steady-State			
Layer 1	17.7	18.0	7.9
Layer 2	8.4	8.0	4.8
Layer 3	5.9	6.0	3.7
Layer 4	5.5	5.0	3.7
Transient-State			
Pre-Colorado River Flooding Calibration			
Layer 1	9.8	9.5	6.0
Layer 2	4.6	3.0	4.1
Layer 3	4.1	3.0	3.6
Layer 4	4.8	4.0	4.1
Colorado River Flooding and Post-Flooding Calibration			
Layer 1	6.9	5.0	6.8
Layer 2	3.4	2.0	4.2
Layer 3	3.4	3.0	3.4
Layer 4	3.8	3.0	3.8

Notes:

Steady-state: calibrated final water levels minus March 1978 water levels
Pre-Colorado River: calibrated final water levels minus March 1983 water levels
Post-Colorado River: calibrated final water levels minus March 1989 water levels

Yuma Valley near Hacienda Estates subdivision (i.e., Zone 2) and over simulated water levelsan average of 3 feet above measured water levels in the western part of Yuma Mesa (i.e., Zone 3). Refer to Table 25 for a statistical analysis of the absolute difference between the final calibrated heads and measured water levels for March 1978 within each of the three zones for selected model layers.

The transient-state was calibration was divided into periods: pre-Colorado River flooding (i.e., October 1978 through March 1983) and post-Colorado River flooding (i.e., April 1983 through March 1989). The pre-Colorado River flooding calibration period simulated the model-wide regional groundwater flow directions and elevations reasonably well in model layers 2, 3, and 4 (i.e., within an average of four to five feet compared to measured water levels) and fairly well in layer 1 (i.e., within an average of 10 feet compared measured water levels). The post-Colorado River flooding calibration period simulated the model-wide regional groundwater flow directions and elevations very well in model layers 2, 3, and 4 (i.e., within an average of three to four feet compared to measured water levels) and fairly well in layer 1 (i.e., within an average of seven feet compared measured water levels). Table 24 presents a statistical analysis of the model-wide absolute difference between the final calibrated heads versus the measured water levels from March 1989 for each model layer. Figures 37 through 40 illustrate where the model simulates measured water levels most accurately during the post-Colorado River flooding calibration period (ie., a map of the error in the calibrated model solution).

The model simulates water levels more accurately in certain locations which is illustrated when comparing simulated water levels within each of the three selected zones to measured water levels. For both the pre-Colorado River flooding and post-Colorado River flooding calibration periods the model over simulated water levels by less than an average of 1 foot compared with measured water levels in the south-western part of Yuma Valley (i.e., Zone 1). The model over simulated water levels an average of 1 foot in the north-eastern part of Yuma Valley (i.e., Zone 2) and under simulated water levels an average of five feet on the Yuma Mesa (i.e., Zone 3). Refer to Table 25 for a statistical analysis of the absolute difference between the final calibrated heads and measured water levels for March 1983 and March 1989 within each of the three zones for selected layers.

Table 25
Statistical Analysis of Zoned Water Level Difference
Steady-State and Transient-State Calibration

Absolute (ABS) Difference of (Calibrated Water Levels
Minus the Measured Ending Water Levels)

	Mean ABS Difference (feet)	*Median of ABS Difference (feet)*	*Standard Deviation of ABS Difference (feet)*
Steady-State			
Zone 1			
Layer 3	3.0	2.8	0.7
Zone 2			
Layer 2	1.1	1.0	0.9
Layer 3	6.4	6.0	1.6
Zone 3			
Layer 1	4.8	3.6	4.0
Transient-State			
Pre-Colorado River Flooding Calibration			
Zone 1			
Layer 3	0.9	0.8	0.6
Zone 2			
Layer 2	1.1	1.0	0.9
Layer 3	1.4	1.0	1.2
Zone 3			
Layer 1	4.8	3.6	4.0
Colorado River Flooding and Post-Flooding Calibration			
Zone 1			
Layer 3	0.9	0.9	0.6
Zone 2			
Layer 2	1.1	1.0	0.9
Layer 3	1.1	0.7	1.0
Zone 3			
Layer 1	4.8	3.6	4.0

Notes: ZONE 1: Located in the south-western part of Yuma Valley between Morelos Dam and Southern International Boundary along the Colorado River (Figure 36)
ZONE 2: Located in the north-east portion of Yuma Valley, encompasses Hacienda Estates subdivision (Figure 35)
ZONE 3: Located in the western portion of Yuma Mesa (Figure 36)
Steady-state: calibrated final water levels minus March 1978 water levels
Pre-Colorado River: calibrated final water levels minus March 1983 water levels
Post-Colorado River: calibrated final water levels minus March 1989 water levels

CHAPTER VII. SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to determine how sensitive the model solution is to uncertainty in each input component. As is generally the case with numerical models, not all of the input components were known completely (i.e., uncertainty with the original data). The purpose of a sensitivity analysis is to determine which input components exert the most control over the model solution and, therefore, generate the largest potential errors. An improved understanding (i.e., reduction of the uncertainty) of the most influential input components would yield the greatest improvement for future model inputs.

The procedure to test the sensitivity of the model consisted of changing a single input component over a reasonable range of values during a series of model runs. The post-Colorado River flooding transient calibrated model was used for the sensitivity analysis. The input components that were changed included recharge due to agricultural irrigation, coarse gravel aquifer (model Layer 4) transmissivity, hydraulic conductivity, specific yield, vertical conductance, evapotranspiration from phreatophytes and boundary conditions. These components were selected since they are the major input variables of the model.

As previously mentioned, three zones were identified within the model domain to evaluate the model sensitivity (Figure 36). Three measures were used to evaluate the model sensitivity within each zone. Two measures were the mean and standard deviation of the final post-Colorado River flooding calibrated water levels minus the simulated water levels for each sensitivity run in each selected zone. The third measure was the volumetric water budgets for each sensitivity run compared to the final calibrated water budget. Tables 26 and 27 compare the mean and standard deviation of water level changes within the selected zones and the percent change in storage from the final calibrated volumetric water budget.

Discussed below is the model-wide sensitivity response to changes in each of the model input components and the statistical analysis within each of the three zones. Decreasing the volume of recharge from agricultural irrigation by 10 and 25 percent created water level elevations to decline throughout the entire model. Water levels declined between one foot and 10 feet with the largest decline occurring beneath the Yuma Mesa (Tables 26 and 27). The

Table 26
Summary of Zoned Sensitivity Statistical Analysis Zones 1 and 2 Combined (Yuma Valley)

Sensitivity Simulated Water Levels Minus Final Post-Colorado River Flooding Water Levels **
(Feet)

Model Input Parameters	LAYER 1		LAYER 2		LAYER 3		LAYER 4		Percent Change in Storage
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	
Decrease Recharge, 10%	N/A	N/A	-0.75	0.27	-0.5	0.18	-0.5	0.07	43%
Decrease Recharge, 25%	N/A	N/A	-1.9	0.66	-1.3	0.44	-1.3	0.44	207%
Decrease Transmissivity, x5	N/A	N/A	-0.65	2.3	0.75	2.3	0.76	2.4	-16%
Increase Transmissivity, x5	N/A	N/A	-3.8	1.1	-3.1	0.99	-3.1	1.0	+559%
Increase VCONT, x2	N/A	N/A	0.02	0.45	0.20	0.13	0.33	0.14	-21%
Increase VCONT, x5	N/A	N/A	0.48	0.81	0.54	0.41	0.74	0.34	-60%
Decrease VCONT, x2	*	*	*	*	*	*	*	*	*
Decrease Sy, x5	N/A	N/A	-1.4	0.32	-1.7	0.15	-1.7	0.49	+7%
Increase Sy, x5	N/A	N/A	1.3	0.42	1.9	0.33	1.9	0.23	-89%
Decrease K, x2	N/A	N/A	-0.29	0.22	0.43	0.32	0.44	0.30	
Decrease K, x5	N/A	N/A	0.52	0.39	0.31	0.40	0.31	0.38	-50%
Increase K, x5	N/A	N/A	1.2	0.72	1.2	0.59	1.2	0.52	-28%
Decrease ET, x5	N/A	N/A	0.19	0.08	0.30	0.09	0.29	0.07	-15%
Increase ET, x5	N/A	N/A	-0.73	0.25	-1.2	0.28	-0.38	0.24	+53%
Boundary Conditions	N/A	N/A	0.01	0.00	0.59	0.22	0.59	0.22	-45%

Notes: ** All differences are changes between the calibrated water levels or water budget component and the sensitivity run.

Sy = Specific Yield
K = Hydraulic Conductivity
Std Dev = Standard Deviation
* Model simulation did not close

N/A = Not applicable
ET = Evapotranspiration
Change in Storage = percent difference from the calibrated change in storage for the entire model

Table 27
Summary of Zoned Sensitivity Statistical Analysis Zone 3 (Yuma Mesa)

Sensitivity Simulated Water Levels Minus Final Post-Colorado River Flooding Water Levels **
(Feet)

Model Input Parameters	LAYER 1		LAYER 2		LAYER 3		LAYER 4	
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Decrease Recharge, 10%	-3.8	0.31	-3.4	0.25	-3.2	0.24	-3.2	0.24
Decrease Recharge, 25%	-9.5	0.78	-8.6	0.63	-8.2	0.60	-8.1	0.60
Decrease Transmissivity,x5	27	2.6	30	3.9	31	4.4	32	4.4
Increase Transmissivity,x5	-28	3.8	-32	3.9	-32	3.3	-33	3.4
Increase VCONT, x2	-3.8	1.0	-0.7	0.25	0.35	0.29	0.75	0.24
Increase VCONT, x5	-6.2	1.9	-1.2	0.46	0.47	0.42	1.1	0.37
Decrease VCONT, x2	*	*	*	*	*	*	*	*
Decrease Sy, x5	-2.1	0.64	-1.7	0.52	-1.6	0.48	-1.6	0.47
Increase Sy, x5	1.1	0.41	0.8	0.43	0.69	0.46	0.67	0.45
Decrease K, x2	3.2	1.3	2.6	0.85	2.4	0.73	2.2	0.68
Decrease K, x5	5.9	2.9	4.7	1.7	4.2	1.4	4.0	1.3
Increase K, x5	-10	2.9	-9.2	2.1	-8.8	1.9	-8.5	1.8
Decrease ET, x5	0.08	0.04	0.08	0.04	0.08	0.04	0.08	0.04
Increase ET, x5	-0.28	0.08	-0.31	0.07	-0.32	0.07	-0.32	0.07
Boundary Conditions	0.11	0.32	0.11	0.32	0.11	0.32	0.11	0.32

Notes: ** All differences are changes between the calibrated water levels or water budget component and the sensitivity run.

Sy = Specific Yield
K = Hydraulic Conductivity
* Model simulation did not close

Std. Dev. = Standard Deviation
ET = Evapotranspiration

volume of water released from storage increased with the lowering of recharge as indicated by the volumetric water budget (Table 26).

Changing the coarse-gravel aquifer (i.e., model Layer 4) transmissivity by a factor of 5 impacted water level elevations in all four model layers, with the greatest impact beneath Yuma Mesa (i.e., water elevation changes between 27 and 33 feet). Lowering transmissivity increased water level elevations while raising transmissivity decreased water level elevations (Tables 26 and 27). This sensitivity is probably attributed to the simulation of the buried bedrock ridges beneath the Yuma Mesa (i.e., ridges of low transmissivity).

Changes in the vertical conductance between all model layers (VCONT) primarily impacted model Layer 1 beneath Yuma Mesa. Attempts at lowering VCONT by a factor of two prevented the model solution from reaching the closure criteria. However, raising VCONT between all model layers by a factor of 5 caused water levels in model Layer 1 to drop up to six feet in elevation while other layers dropped less than one foot beneath the Yuma Mesa (Tables 26 and 27). Water levels in the Yuma Valley were relatively insensitive to increases in VCONT. The model's sensitivity to VCONT confirms the conceptual model that the hydrogeologic system essentially behaves as one aquifer with each geologic unit having markedly different hydrologic characteristics.

Changes in horizontal hydraulic conductivity in model layers 1, 2, and 3 had a relatively minor impact on water levels throughout the model except beneath the Yuma Mesa. Lowering the horizontal hydraulic conductivity by a factor of five increased water levels up to six feet beneath the Yuma Mesa in all model layers. However, raising the horizontal hydraulic conductivity by a factor of five decreased the water level elevations beneath the Yuma Mesa by 10 feet (Tables 26 and 27). The sensitivity of model Layer 1 probably indicates the calibrated hydraulic conductivity values are at their maximum range beneath the Yuma Mesa and could not be increased. However, a decline in hydraulic conductivity values by only a factor of two would cause a relatively minor change in water levels beneath both the Yuma Mesa and Yuma Valley.

Changes in specific yield within all model layers had a relatively minor impact on water levels throughout the model. Water level elevation changes were less than two feet when the specific yield was increased or decreased by a factor of five (Tables 26 and 27). However, when increasing specific yield, the volume of water in storage increased significantly (Table 24).

Changes in evapotranspiration (ET) rate had a effect on water level elevations adjacent to the Colorado and Gila Rivers only. Water levels within the three zones were impacted minimally (i.e., less than 0.1 feet). However, increasing ET decreased the volume of groundwater in storage as indicated by the volumetric water budget (Table 26).

Changing the model western and southern boundary cells from constant head to variable head had a marked effect on water levels adjacent to the boundaries. Groundwater underflow from the model boundaries were held constant at the final calibrated underflow estimates simulated in the post-Colorado River flooding calibration. Water levels increased approximately 6 feet along the western border and 3 feet along the southern border. However, the impacts of the water level increases were only evident within Mexico and had little to no impact within the United States portion of the model domain (Tables 26 and 27). These water level rises can be attributed to either the initial constant head elevations were estimated too low or the volume of underflow out the model boundaries was incorrectly distributed. This simulation confirmed that the design of the model boundaries has little effect on the accuracy of the model solution in the northern portion of Yuma Valley and western portion of Yuma Mesa.

In summary, comparing the mean deviation of the zoned calibrated water levels minus the sensitivity water levels indicate that, in general, model Layer 1 beneath the Yuma Mesa is most sensitive to input parameter changes. The model is most sensitive to changes in coarse-gravel aquifer (i.e., model Layer 4) transmissivity, decreases in recharge and VCONT and increase in horizontal hydraulic conductivity. The Yuma Mesa portion of the model (i.e., Zone 3) is the most sensitive to changes in input components while the Yuma Valley portion of the model (i.e., Zones 1 and 2) is less sensitive.

CHAPTER VIII. SCENARIOS SIMULATIONS

Introduction

The Yuma area groundwater flow model was utilized to quantitatively evaluate the effects from several model scenario simulations on the groundwater system. The Overview Committee, which was established in October 1990, discussed and developed nine scenario simulations. These simulations can be divided into three categories. First, an initial "base case" simulation was conducted using the final calibrated water year (i.e., April 1988 through March 1989) as a baseline for which to measure change. Second, the model was used to evaluate the impacts of the 1993 Gila River flooding on the groundwater system in an attempt to predict where potential shallow groundwater levels might exist due to this recent flooding. Third, the model was used to evaluate various water management alternatives which address the shallow water level problems near Hacienda Estates subdivision in northern Yuma Valley.

Scenario simulations started when the transient-state model ended in April 1989 and were conducted for eight years through March 1997. All model input data were held constant for the first four years between April 1989 and March 1993 for each scenario simulation using data from the final transient-state calibrated water year (i.e., April 1988 through March 1989). Each scenario stress began in April 1993 and continued either for six months (i.e., April 1993 through September 1993) or for four years (i.e., April 1993 through March 1997). The varying length of each stress was dependant upon the scenario simulation. For example, Gila River flooding scenarios simulated high river flows for six months, while the lining of canals were simulated for four years.

Evaluating the results of each scenario simulation consisted of comparing the relative change in groundwater elevations and water budget components due to each scenario. The changes in groundwater elevation were compared quantitatively within the same three zones used for the sensitivity analysis and compared qualitatively on a regional model-wide basis (Figure 36). The change in groundwater elevations and in water budget components is defined as the difference between the scenario simulation and the "base case" simulation.

The 1993 Gila River flooding scenario was compared to the initial "base case" simulation in an attempt to quantify the impacts of the flooding on the regional groundwater system. All other scenario simulations were then compared to the 1993 Gila River flooding simulation. The Gila River flooding simulation serves as the "new base case" since the effects from this flooding must be taken into account when evaluating the success of any water management alternative on lowering water levels near the Hacienda Estates subdivision. However, the impacts on the groundwater system from the flooding were simulated to be short-term, with no decernible changes in groundwater elevations four years after the flooding ceased.

It is imperative to understand when evaluating the change in groundwater elevation as compared to a "base case" simulation that the relative change is what is important. The relative change is an indicator of how the model responds to a particular set of stresses on the groundwater system. The absolute change in groundwater elevation predicted by the model may not be exactly correct due to the margins of error or uncertainty within the model. However, absolute changes in groundwater elevations were provided to illustrate the relative impacts of each of the scenarios simulated for comparative purposes.

Figures for illustrating the results from the scenario simulations are provided in Appendix IV.

Model Simulations

Initial "Base Case"

An initial "base case" simulation was conducted using model data from the final transient-state calibrated water year (i.e., April 1988 through March 1989). These model input data were held constant throughout the entire eight year simulation to establish a baseline from which to measure the effects of the 1993 Gila River flooding.

1993 Gila River Flooding ("New Base Case")

Three scenario simulations were conducted to evaluate the impacts of the 1993 Gila River flooding on the regional groundwater system. The first scenario consisted of simulating the Gila River flowing an average of 17,000 cubic feet per second (CFS) for six months between April, 1993 and September, 1993. This flow rate was provided by the U.S. Army Corps of Engineers on March 8, 1993 and represents a computer generated projection of the average flow for the six month period (U.S. Army Corps of Engineers, 1993). The projected high flow out of Painted Rock Reservoir was over 24,000 CFS then decreasing down to a constant low flow of 12,500 CFS. This computer generated estimate was used to represent the maximum volume of water flowing through the Yuma area to determine what the greatest effects of the flooding would be on the groundwater system. This scenario also simulated flow in the generally dry Colorado River downstream of Morelos Dam during the same six month period. Stream gaging data downstream of Morelos Dam were used to estimate that the average flow rate below the dam was 15,500 CFS.

The model-wide results of the Gila River flooding simulation indicate that the rise in groundwater levels at the end of the six month period (i.e., September 1993) was between one foot and five feet adjacent to the Gila and Colorado Rivers. This regional impact only occurred within one to two miles away from the river channels. There was a minor rise in groundwater elevations near the Hacienda Estates subdivision at the end of the six month flooding period (i.e., September 1993) as indicated by the statistical analysis of water levels within Zone 2. The average groundwater level rise in model Layer 2 was 0.5 feet (Table 28). This indicates that the six months of Gila River flooding should have a minimal impact on groundwater levels near the subdivision. Table 28 presents the results of the changes in groundwater elevations. Figures 1A and 1B illustrate the change in groundwater level elevations within model Layers 2 and 3, respectively, as compared to the initial "base case" scenario simulation.

It is important to note that changes in groundwater elevations at the end of the 8 year simulation (i.e., March 1997) were negligible. This indicates that the effects of the Gila River flooding on the regional groundwater system should dissipate with time and not have long-term negative impacts.

The actual flows released from the Painted Rock Dam as of August, 1993, ranged from a high of 24,000 CFS to a low of about 2,000 CFS between March and August, 1993 (Earl Burnett, U.S. Bureau of Reclamation, Personal Communication). The average release for this period was about 8,500 CFS, approximately one-half the flow rates projected by the U.S. Army Corps of Engineers on March 8, 1993.

A second Gila River flooding simulation was conducted using the lower average flow release rate of 8500 CFS from Painted Rock Dam. The model-simulated results indicate a similar rise in groundwater levels at the end of the six-month period (September 1993) to the previous scenario run (Figure 1C).

Comparing this simulation with the previous scenario run (ie., 17,000 CFS release from Painted Rock Dam) groundwater elevations also increased adjacent to the Gila and Colorado Rivers, albeit a maximum of three feet and not five feet. The regional impact on the groundwater system from the decreased flows in the Gila River was confined within a narrow band along the river channels (Refer to Figures 1B and 1C).

However, either simulation (i.e. 17,000 CFS or 8500 CFS release from Painted Rock Dam) predicted changes in groundwater elevations at the end of the eight year simulation (i.e., March 1997) to be negligible. This confirms that the effects of the Gila River flooding on the groundwater system should be short-term and the use of either scenario run as a "base case" from which to compare the impacts of other scenario simulations is appropriate.

It is important to note that the change in groundwater level elevations simulated after six months of flooding may not necessarily represent the maximum water level rise. This is because model simulated water levels were only evaluated at the end of six months (i.e., September 1993) and four years (i.e., March 1997) and not at any intermediate time increment due to computer disk storage limitations.

Table 28
Statistical Analysis of Scenario Simulations Within Zones 2 and 3 Only

Scenario	***Scenario Simulation Minus "Base Case" Simulation*** *(Change In Groundwater Elevation - Feet)*									
	Layer 1 (Zone 3) [1]		*Layer 2 (Zone 2)* [2]				*Layer 3 (Zone 2)* [3]			
	1993		**1993**		**1997**		**1993**		**1997**	
	Ave	**Max**	**Ave**	**Max**	**Ave**	**Max**	**Ave**	**Max**	**Ave**	**Max**
1993 Gila R. Flooding	N/A	N/A	+0.5	+1.0	0.0	0.0	0.2	0.8	0.0	0.0
1993 Gila R. Flooding & DW Pumping	N/A	N/A	-0.9	-2.8	-2.5	-8.7	-1.6	-4.8	-6.2	-10.4
Lining East Main Canal	N/A	N/A	N/A	N/A	-0.3	-0.8	N/A	N/A	-0.3	-0.5
Lining East Main Canal & DW Pumping	N/A	N/A	N/A	N/A	-1.8	-6.1	N/A	N/A	-2.2	-6.1
25% Decrease in Ag Recharge on Yuma Mesa	-8.2	-9.2	N/A	N/A	-0.7	-2.4	N/A	N/A	N/A	N/A
25 % Decrease in Ag Recharge in Yuma Valley	N/A	N/A	-0.4	-1.0	-0.5	-1.0	-0.1	-0.3	-0.4	-0.6
Lining All-American Canal	N/A	N/A	N/A	N/A	-0.5	-1.6	N/A	N/A	-0.5	-1.7
Effects of Removing Clay B on Groundwater Mound	-5.7 [4]	-12.5 [4]	N/A	N/A	0.2	0.6	N/A	N/A	0.2	0.5

Notes:
1. Layer 1 (Zone 3) = Represents the upper, fine-grained zone (model Layer 1) on Yuma Mesa. Refer to Figure 36 for location
2. Layer 2 (Zone 2) = Represents the clayey-silt layer (model Layer 2) in Yuma Valley near Hacienda Estates. Refer to Figure 36 for location
3. Layer 3 (Zone 2) = Represents the upper, fine-grained zone (model Layer 3) in the Yuma valley near Hacienda Estates. Refer to Figure 36 for location
4. Represents water level decline after 4 years of removing Clay B - 1997 not 1993

N/A = Not Applicable
AVE = Average change in groundwater elevation
MAX = Maximum change in groundwater elevation

1993 Gila River Flooding and Drainage Well Pumpage

The third scenario simulated to evaluate the impacts of the Gila River flooding was identical to the first (i.e. 17000 CFS release from Painted Rock Reservoir) with the exception of pumping pre-selected drainage wells. All model input parameters discussed in the first scenario simulation were identical in this simulation except for the addition of pumping the drainage wells for four years between April 1993 and March 1997.

Table 29 presents the list of existing drainage wells that the Overview Committee selected. Figure 2A illustrates the areal location of these drainage wells. Each well was assumed to be pumping at its maximum capacity for the entire four years at a cumulative total pumping rate of 51,600 AF/Year. All other groundwater pumpage was held constant to the rates from the final transient-state calibrated year (i.e., April 1988 through March 1989).

The model-wide results of the simulation indicate that groundwater levels decreased in elevation between 3 and 5 feet in the northern portion of Yuma Valley after six months of flooding and drainage well pumping (i.e., September 1993) (Figures 2B and 2C). However, after four years of continued drainage well pumping (i.e., April 1993 through March 1997), groundwater levels decreased in elevation over 7 to 10 feet in the northern portion of Yuma Valley. Figures 2D and 2E illustrate the change in groundwater level elevations within model Layers 2 and 3, respectively, as compared to the 1993 Gila River flooding "new base case" (i.e., 17,000 CFS release from Painted Rock Dam) scenario simulation.

There was a significant change in groundwater levels adjacent to the Hacienda Estates subdivision as indicated by the statistical analysis of water levels within Zone 2. Groundwater levels declined in elevation an average of 1-2 feet after six months of pumping (i.e., September 1993) and after four years an average of 2-6 feet (i.e., March 1997). Table 28 presents the results of the changes in groundwater elevation.

Table 29

Selected Drainage Wells Pumped During 1993 Gila River Flooding Scenario Simulation

DW 1 = 2800 gpm	DW 13 = 1900 gpm
DW 2 = 2400 gpm	DW 14 = 2000 gpm
DW 8 = 450 gpm	DW 15 = 3100 gpm
DW 9 = 2300 gpm	DW 16 = 2400 gpm
DW 10 = 1600 gpm	DW 17 = 4500 gpm
DW 11 = 2200 gpm	DW 18 = 2200 gpm
DW 12 = 1700 gpm	DW 19 = 2500 gpm

Note: - Pumpage rates are the maximum projected capacity provided by the U.S.B.R.

Lining of East Main Canal

This simulation represents the first of several water management alternatives tested to evaluate the success of lowering the shallow groundwater elevations near the Hacienda Estates subdivision. This simulation consisted of lining four miles of the East Main canal adjacent to the subdivision between April 1993 and March 1997. All other model input parameters are identical to the "new base case" simulation (i.e., 1993 Gila River flooding) except for the lining of the canal.

The lining of the canal was simulated between County 9.5 Street and County 13.5 Street (Figure 2A). Calibrated seepage losses of 700 AF/Mile/YR were eliminated by reducing the vertical hydraulic conductivity of the canal bottom sediments to zero. This reduced seepage losses from this portion of the East Main canal by 2800 AF/Year.

The results of this simulation indicate that groundwater levels decreased in elevation adjacent to the Hacienda Estates subdivision a maximum of almost one foot after six months (i.e., September 1993). The areal extent of these groundwater level declines was limited to immediately adjacent to the canal (Figures 3A and 3B). However, the effects of lining the canal after four years (i.e., March 1997) is not significantly different than after six months, except that the areal extent of the declines has slightly spread out away from the canal (Figure 3C). Table

28 presents a statistical analysis of groundwater level declines as compared to the "new base case" (ie., 17,000 CFS release from Painted Rock Dam) 1993 Gila River flooding scenario.

Lining of East Main Canal and Drainage Well Pumping

The second simulation regarding lining of the East Main canal was identical to the first except for the addition of pumping existing drainage wells. All model input parameters discussed in the previous scenario were identical in this simulation except for the drainage well pumping.

Drainage wells DW 14 and DW 15 were selected to be pumping during this simulation. Figure 4A illustrates the areal location of these wells. Each well was assumed to be pumping at its maximum capacity for four years at a total withdrawal of approximately 8,200 AF/Year. All other groundwater pumpage was held constant to the rates from the final transient-state calibrated water year (i.e., April 1988 through March 1989).

The results of this simulation indicate that the effects on the groundwater system from pumping overshadow the effects from lining the canal and have the greatest impact on lowering groundwater levels near the Hacienda Estates subdivision. Groundwater levels declined between one and three feet after six months of pumping the drainage wells (i.e., September 1993). However, groundwater levels declined a up to six to seven feet after four years (Figures 4A and 4B). Table 28 presents the statistical analysis of groundwater level declines as compared to the "new base case" 1993 Gila River flooding scenario.

Reduction of Deep Percolation Recharge on Yuma Valley

Two water management alternatives simulated the decrease in recharge from deep percolation of agricultural irrigation within both the Yuma Valley and Yuma Mesa subareas. This simulation involved decreasing recharge by 25 percent from calibrated estimates within the northern portion of Yuma Valley only. Recharge rates from agricultural irrigation was reduced from an average of 1 AF/AC/Year to 0.75 AF/AC/Year north of County 14th Street within Yuma Valley. This reduced the total volume of recharge to the groundwater system by only 3,600 AF/Year. It must be noted that this simulation does not take into account the areal distribution of crop types such as lettuce, broccoli or cauliflower. Since the reduction of recharge is a blanket change, this simulation may not accurately reflect exact locations where shallow groundwater levels might exist.

The model-wide results of this simulation indicate that groundwater levels decreased in over one foot in certain locations within the Yuma Valley after four years (i.e., March 1997). Figures 5A and 5B illustrate the change in groundwater level elevations within model Layers 2 and 3, respectively, as compared to the "new base case" 1993 Gila River flooding simulation (i.e., 17,000 CFS release from Painted Rock Dam). Groundwater elevations experienced an average decline of 0.5 feet after four years near Hacienda Estates subdivision as indicated by the statistical analysis of water levels within Zone 2 (Table 28).

Reduction of Deep Percolation Recharge on Yuma Mesa

The second water management alternative that simulated the decrease in recharge from deep percolation of agricultural irrigation involved the Yuma Mesa. This simulation reduced recharge from the calibrated estimates from both major irrigation districts on the Yuma Mesa (i.e., Yuma Mesa I.D. and Unit B I.D.). Calibrated recharge rates for Yuma Mesa I.D. (7.5 AF/AC/Year) and Unit B I.D. (6.9 AF/AC/Year) were reduced by 25 percent for the entire Yuma Mesa area. This reduced the total volume of recharge to the groundwater system by approximately 50,000 AF/Year.

The model-wide results of the simulation indicate that groundwater levels decreased over nine feet after four years in model Layer 1 (i.e., March 1997) as compared to the "new base case" 1993 Gila River flooding simulation (Figure 6A). The regional effects of this reduced recharge on groundwater level elevations in the Yuma Valley and South Gila Valley are illustrated in Figures 6B and 6C. These figures show a decrease in water levels of approximately one to two feet in both model Layers 2 and 3 adjacent to Hacienda Estates and the South Gila Valley.

The statistical analysis of water levels within Zone 3 indicate that water levels declined an average of eight feet on Yuma Mesa after four years (Table 28). This drop in water levels equals a decline rate of approximately 2 FT/YR on Yuma Mesa by only decreasing recharge from deep percolation of agricultural recharge 25 percent.

It must be noted that the Yuma Mesa drainage wells that were pumping in 1988/89 were also pumping during this simulation. To accurately simulate the maximum effects of the groundwater mound on water levels adjacent to Hacienda Estates subdivision, these Yuma Mesa drainage wells should be turned off.

Lining of All-American Canal

This simulation represents the water management alternative of lining the entire length of the All-American canal within the Yuma area. Twenty-six miles of the canal was simulated to be lined beginning in April 1993 through March 1997. All other model input parameters are identical to the "new base case" 1993 Gila River flooding simulation (i.e., 17,000 CFS release from Painted Rock Dam) except for the lining of the canal.

The lining of the canal was simulated between Laguna Dam and the downstream model boundary several miles west of Pilot Knob Power Plant (Figure 7A). Seepage losses from the canal are the highest of any canal within the Yuma area and were calibrated at 2,700 AF/Mile/Year. These losses were eliminated by reducing the vertical hydraulic conductivity of the canal bottom sediments to zero.

The results of this simulation indicate that model-wide groundwater levels decreased significantly within the Reservation and Bard irrigation districts after four years (i.e., March 1997) as compared to the "new base case" 1993 Gila River flooding simulation (Figures 7B and 7C). The greatest water level declines occurred on the north side of the Colorado River adjacent to the canal. This area experienced water level declines of up to eight to nine feet. Several drains experienced decreased flow within the Reservation and Bard irrigation districts, and the Araz drain dried up all together. Groundwater discharge into the Colorado River was also affected by lining the canal. Groundwater discharge into the river decreased approximately 10,000 AF/Year between Laguna and Morelos Dams.

Groundwater levels also declined up to one to four feet in the northern portion of Yuma Valley. The hydrologic influence of lining the All-American canal within the Yuma Valley can be attributed to the fact that the Colorado River only partially penetrates the aquifer within the Yuma area. This hydrologic condition permits a significant component of groundwater underflow beneath the Colorado River.

Groundwater level elevations experienced an average decline 0.5 feet as indicated by the statistical analysis of water levels within Zone 2 (Table 28). However, these declines were contained primarily within the northern part of Zone 2 and not adjacent to the Hacienda Estates subdivision.

Effects of Clay B on Yuma Mesa Groundwater Mound

As previously discussed in Chapter 2, a clay zone beneath the Yuma Mesa has been informally identified by Olmsted and others (1973) as Clay B. This clay layer is aerially extensive and laterally continuous with the silt and clay layer that comprises the river valley land surface (Figure 7). Clay B is thought to play an important role hydrologically by inhibiting the vertical movement of groundwater flow beneath the Yuma Mesa. This simulation evaluates the effects of removing the hydraulic characteristics of Clay B between April 1993 and March 1997. This was accomplished in two steps. First by replacing the horizontal hydraulic conductivity of Clay B with that of the upper, fine-grained zone (or model Layer 3). Second, and most important, the vertical hydraulic conductivity or VCONT, was replaced with the value calculated between model Layers 3 and 4. Changing both of these hydraulic characteristics quasi-simulated the hydrogeology as if Clay B was not there.

The model-wide results of this simulation indicate that the hydraulic characteristics of Clay B have a great impact on creating the groundwater mound beneath the Yuma Mesa. Groundwater levels decreased over 16 feet in four years beneath the Yuma Mesa as compared to the "new base case" 1993 Gila River flooding simulation. This drop in water levels equals a decline rate of 4 FT/YR assuming the recharge rates for 1988/89 were held constant. Figures 8A, 8B and 8C illustrates the groundwater level declines for model Layers 1, 2, and 3 respectively.

Conclusions

The Yuma area groundwater flow model was utilized to quantitatively evaluate the effects on the groundwater system from several model scenario simulations. Each simulation was conducted for eight years starting where the transient-state calibrated model ended in April 1989 and continued through March 1997. All model input data were held constant for the first four years between April 1989 and March 1993 using data from the final calibrated water year (i.e., April 1988 through March 1989). Each scenario stress began in April 1993 and continued for either six months or four years depending upon the scenario.

These simulations were divided into three categories. First, an initial "base case" simulation was conducted using the final calibrated water year (i.e., April 1988 through March 1989) as a baseline from which to measure change. Second, the model was used to evaluate the impacts of the 1993 Gila River flooding on the groundwater system. Third, the model was used to evaluate various water management alternatives which address the shallow water level problems near Hacienda Estates subdivision in northern Yuma Valley.

An initial "base case" simulation was conducted using model input data from the final transient-state calibrated water year (i.e., April 1988 through March 1989). These model input data were held constant throughout entire eight year simulation to establish a baseline from which to measure the impacts from the 1993 Gila River flooding.

Three scenario simulations were conducted to evaluate the impacts of the 1993 Gila River flooding on the regional groundwater system. The first scenario consisted of simulating the Gila River flowing an average of 17,000 CFS for six months as predicted by the U.S. Army Corps of Engineers on March 2, 1993. This scenario was compared to the initial "base case" and predicted that water levels would rise between one and five feet in a relatively narrow band (i.e., less than two miles) adjacent to the Colorado and Gila River channels after six months of flooding. This simulation predicted that the impacts of the flooding would not significantly impact groundwater elevations where most of the urbanization exists in northern Yuma Valley. This scenario became the "new base case" for which all other scenario simulations are compared since the flooding has effected the regional groundwater system.

The second simulation was identical to the first but took advantage of more recent flow release data from Painted Rock Dam. This scenario run simulated the actual average flow rate released from Painted Rock Dam of 8,500 CFS for the six month period between March and September 1993. The results were compared to the "base case" simulation and predicted water levels would rise between one and three feet in a relatively narrow band (i.e., less than 1.5 miles) adjacent to the Gila and Colorado Rivers.

It must be noted that neither of the two Gila River flooding scenarios (i.e., 17,000 CFS or 8500 CFS release from Painted Rock Dam) simulated any significant groundwater elevation changes four years (i.e., March 1997) after the flooding ceased as compared to the "base case" simulation. Therefore, it was determined that comparing all other scenario runs to the initial flooding simulation (i.e., 17,000 CFS) would still yield valuable results for evaluating which water management would be most effective in lowering groundwater levels in northern Yuma Valley.

The third Gila River flooding scenario was identical to the first simulation (i.e., 17,000 CFS release from Painted Rock Dam) except 14 existing drainage wells were pumped during the flooding. These drainage wells significantly decreased groundwater level elevations in the northern Yuma Valley as compared to the "new base case" simulation. The model predicted that pumping these wells should prevent any potential groundwater level rises due to the flooding.

Various water management alternatives were simulated to evaluate which would be the most effective in lowering water levels adjacent to the Hacienda Estates subdivision. The first simulation consisted of lining four miles of the East Main canal adjacent to the subdivision between County 9.5 Street and County 13.5 Street. Eliminating the seepage from this portion of the East Main canal had a relatively minor effect on lowering water levels near Hacienda Estates. After four years, groundwater levels near the subdivision decreased in elevation approximately 0.5 to one foot as compared to the "new base case" simulation.

The second simulation concerning the East Main canal was identical to the first except specific drainage wells were pumped. The wells, DW 14 and DW 15, are located near the Hacienda Estates subdivision. The impacts on the groundwater system from pumping these wells overshadowed the effects from lining the canal and has the greatest effect on lowering groundwater levels of all the scenario simulations conducted. Water levels declined an average of over two feet and a maximum up to seven feet after four years of pumping.

The next two water management alternatives simulated to lower the water levels near Hacienda Estates addressed decreasing recharge from deep percolation of excess agricultural irrigation. The first simulation lowered recharge within the northern portion of Yuma Valley by 25 percent (i.e., north of County 14 Street). The model predicted that water levels would decline an average of 0.5 to one foot after four years near Hacienda Estates as compared to the "new base case" simulation. However, since this simulation does not take into account the aerial distribution of water intensive crops (e.g., lettuce and other vegetables), specific locations of shallow water levels may not be accurately simulated.

The second simulation evaluating the effects of reducing recharge from excess agricultural irrigation involved the Yuma Mesa. Recharge from both Yuma Mesa I.D. and Unit B I.D. were reduced by 25 percent for the entire Yuma Mesa area. The model predicted the groundwater mound would decrease over eight feet after four years as compared to the "new base case" simulation. The model also predicted that decreasing water levels beneath Yuma Mesa would impact groundwater levels in eastern Yuma Valley and southern South Gila Valley. Water levels in these areas were predicted to decrease one to two feet after four years. Although this simulation predicts significant water level declines beneath the Yuma Mesa, it may not represent the maximum effect the groundwater mound has on water levels in Yuma Valley. This is because the Yuma Mesa drainage wells that were pumping in 1988/89 were also pumping during this simulation.

The last water management scenario addressing the shallow water levels near Hacienda Estates focused on lining the entire reach of the All-American canal within the Yuma area. This scenario simulated lining twenty-six miles of the canal from Laguna Dam to west of Pilot Knob Power Plant. Seepage losses from this canal are the greatest of any canal within the Yuma area, and lining the canal had a significant impact on groundwater elevations in the Reservation and Bard irrigation districts.

The model predicted that water levels adjacent to the canal would decrease up to nine feet after lining the canal for four years as compared to the "new base case" simulation. Several drains experienced decreased flow within the Reservation and Bard irrigation districts, and the

Araz drain dried up completely. Groundwater discharge into the Colorado River between Laguna and Morelos Dams also decreased by an average of 10,000 AF/Year. Lining of the canal also had an impact on the south side of the Colorado River in the northern portion of Yuma Valley. Water levels in Yuma Valley experienced a decline of one to four feet after four years. These declines can be attributed to the significant component of groundwater underflow beneath the river since it does not fully penetrate the aquifer.

The final scenario evaluated the impact of Clay B on the development of the groundwater mound beneath the Yuma Mesa. This scenario simulated the replacement of the horizontal and vertical hydraulic conductivity of Clay B to that of the upper, fine-grained zone. The model predicted that Clay B plays a major role in inhibiting the downward vertical movement of groundwater beneath the Yuma Mesa. Groundwater levels decreased in elevation over 16 feet within four years as compared to the "new base case". This drop in elevation indicates that the existence of Clay B in conjunction with the recharge of excess agricultural irrigation water play a major part in the development of the groundwater mound beneath the Yuma Mesa.

Model Reliability and Limitations

There are several factors that affect the reliability of the numerical model constructed for the Yuma area. These factors must be considered when evaluating the calibration results or utilizing the model for future scenario predictive purposes. The factors include the level of uncertainty of the original input data, the analysis of the calibrated error between model simulated and measured water levels, and the sensitivity of certain model input parameters and their influence on the accuracy of the model solution. In conjunction with these factors, certain simplifying assumptions were necessary to represent the conceptual model of the groundwater flow system within the framework of the numerical model. Most of the assumptions used to develop the model have been fully discussed and justified previously. However, it is important to understand these assumptions when evaluating the reliability and limitations of the model. The primary assumptions are:

1. Water levels in all model layers (i.e., all hydrogeologic units) were initially assumed to be identical in elevation (except beneath the All-American canal where

the water level was simulated to be perched above the regional groundwater system). This hydrologic condition may not have accurately simulated the three-dimensional nature of the groundwater system.

2. Hydraulic heads computed within each model cell represents the average head within the volume of that cell. Model cell size is critical to the accuracy of simulating the real groundwater system. Each model cell ranges in area between 40 acres and 640 acres and varies in thickness from a few feet to several tens of feet. In general, the smaller the cell size the more accurate the water level simulated.

3. Calculation of the surface water stage elevation in model cells that contain surface water features (e.g., river, canal, or drain) simulated by the streamflow-routing package is based upon a rectangular channel and Manning's equation. The width of the surface water feature also is assumed to be much greater than the depth (Prudic, 1989). This assumption may not be appropriate for all surface water features within the Yuma area and may have an influence on the simulated flux between the surface water feature and the groundwater system.

4. The accuracy of the model to simulate actual water level changes due to stresses on the groundwater system (e.g., Gila River flooding) is unknown and will be proven with time and model use. However, the model seems to reasonably simulate the flooding and its potential effects on the groundwater system, especially when comparing the effects four years after the flooding ceased. It is assumed that the model is sufficiently accurate to compare and evaluate the results from other scenario simulations to determine which would be the most effective in lower water levels in northern Yuma valley.

In conjunction with these assumptions and factors that influence the model's capability to accurately simulate the groundwater flow system, the model has several limitations. The limitations of the model are summarized below:

1. The model's capability to accurately simulate groundwater flow conditions is better in some areas than in others. These areas were determined by the analysis

of the error between the simulated and measured water levels and are illustrated in Figures 37 through 40. It is important to refer to these figures when evaluating the reliability of the model solution.

2. Groundwater return flow simulated to the Colorado and Gila Rivers are reasonable approximations, however, they must be evaluated within the contexts of the assumptions discussed above.

CHAPTER IX. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

In general, the groundwater flow model developed for the Yuma area reasonably simulates steady-state (1978) and transient-state (1978-1989) groundwater flow conditions. The model is a sound technical tool for analyzing the complex three-dimensional interrelationship between the groundwater and surface water systems. The model is also useful for evaluating the impacts from various water management alternatives on the hydrologic system to determine which would be most effective in lowering groundwater levels in the Hacienda Estates subdivision.

The specific conclusions of this modeling effort are:

1. The Colorado River flooded the Yuma area between 1983-84 and became a source of recharge to groundwater system. The high flood stages prevented the groundwater system from naturally draining to the river. The inability of the groundwater system to discharge to the river compounded the already shallow groundwater levels that existed adjacent and away from the river. However, this effect was short term due to the very high permeability of the sediments in the Yuma area.
2. In conjunction with the Colorado River flooding, change in crop types exacerbated the already shallow water levels away from the river. Agricultural recharge from these vegetable crops prevented groundwater levels from subsiding even after the Colorado River flows subsided to pre-flood conditions.
3. The shallow water levels near the Hacienda Estates subdivision are the result of several factors. These factors include: the area has been historically an area of shallow groundwater levels, changes in crop types in the Yuma Valley to more vegetable crops, effects of the groundwater mound beneath the Yuma Mesa, seepage from the unlined East Main canal, and to a much lesser degree the short-term transient effects from the flooding of the Colorado River.

   Although each of these factors has contributed to the historical shallow water level problem, several of these factors play a much more important role today. The model simulated the relative impacts from each of these factors (Table 28). The greatest impact on water levels near the Hacienda Estates subdivision today are from the deep percolation from excess agricultural irrigation in the Yuma Valley and on Yuma Mesa and the seepage from the East Main canal. However, the model could not accurately simulate their maximum effects on the groundwater system due to data limitations.

4. The groundwater flow model predicted that the 1993 Gila River flooding should have a minimal impact on groundwater levels beyond two miles away from the river. The existing drainage well network should be sufficient to prevent the urbanized portions of Yuma Valley from being affected by rising groundwater levels due to the flooding by the Gila River.

5. The groundwater flow model effectively simulated various water management alternatives to address the shallow groundwater levels adjacent to Hacienda Estates subdivision. The results are:

   A. The model predicted that lining the East Main canal and pumping drainage wells DW 14 and DW 15 would have the greatest impact on lowering groundwater levels near the Hacienda Estates subdivision. This simulation predicted that groundwater levels would decline an average of over two feet and a maximum of seven feet after four years of pumping.

   B. The model predicted that lining four miles of the East Main canal adjacent to Hacienda Estates would lower groundwater levels approximately one foot after four years.

   C. The model predicted that reducing deep percolation from excess agricultural irrigation by 25 percent within Yuma Valley would lower groundwater levels near Hacienda Estates approximately one foot or more.

   D. The model predicted that reducing deep percolation from excess agricultural irrigation by 25 percent on Yuma Mesa would impact water levels in eastern Yuma Valley and southern South Gila Valley. Water levels would decline approximately one to two feet in Yuma Valley and an average of eight feet beneath Yuma Mesa after four years.

E. The model predicted that lining 26 miles of the All-American canal within the Yuma area would decrease water levels up to nine feet adjacent to the canal, and from one to five feet in the Reservation and Bard irrigation districts after four years. This simulation predicted that groundwater levels would decline an average of 0.5 feet in the northen portion of Yuma Valley near Hacienda Estates.

Recommendations

This modeling effort identified the need for local agencies to coordinate, evaluate and plan for long-term water management in the Yuma area to prevent shallow groundwater levels from becoming more of a problem. The recommendations should assist local planners in evaluating the most effective alternative in decreasing water levels at the lowest cost. These recommendations are:

1. Couple the results of the model scenario simulations with a cost-to-benefit economic analysis. This would assist in evaluating which of the alternatives to lowering water levels near Hacienda Estates subdivision is actually the most economical.
2. Local agencies that gather hydrologic, cropped acreage, water applied and other types of data should coordinate and adopt a standard format and deposit this data into one repository. This would greatly enhance future efforts to update the groundwater flow model and assist in any future water management planning or data collection efforts.
3. Several data deficiencies were identified which may increase the success of future modeling efforts. These deficiencies include:

   A. Better definition of the aerial location of where crops are grown. This information would increase the accuracy of future modeling efforts. The aerial location of where to attribute recharge from excess irrigation is very important when attempting to predict where shallow groundwater levels might exist in the future.

B. Conduct a seepage test along the East Main canal to better understand the hydraulic interconnection between the canal and groundwater system near the Hacienda Estates subdivision.

C. The need for water level data for the coarse gravel zone to better define the vertical distribution of hydraulic head.

D. The need for vertical hydraulic conductivity data for the Clay B and upper, fine grained zone beneath the Yuma Mesa. This data would better define the relationship of the groundwater mound and the hydrogeologic influence.

E. The need for groundwater levels within Mexico that are representative of the same aquifer as the water levels obtained within the United States. This data would assist in quantifying the groundwater underflow out of the United States.

F. Site specific pumpage data from Mexico. This data would assist in defining hydrologic conditions in Mexico and help quantify the effects on groundwater underflow out of the United States.

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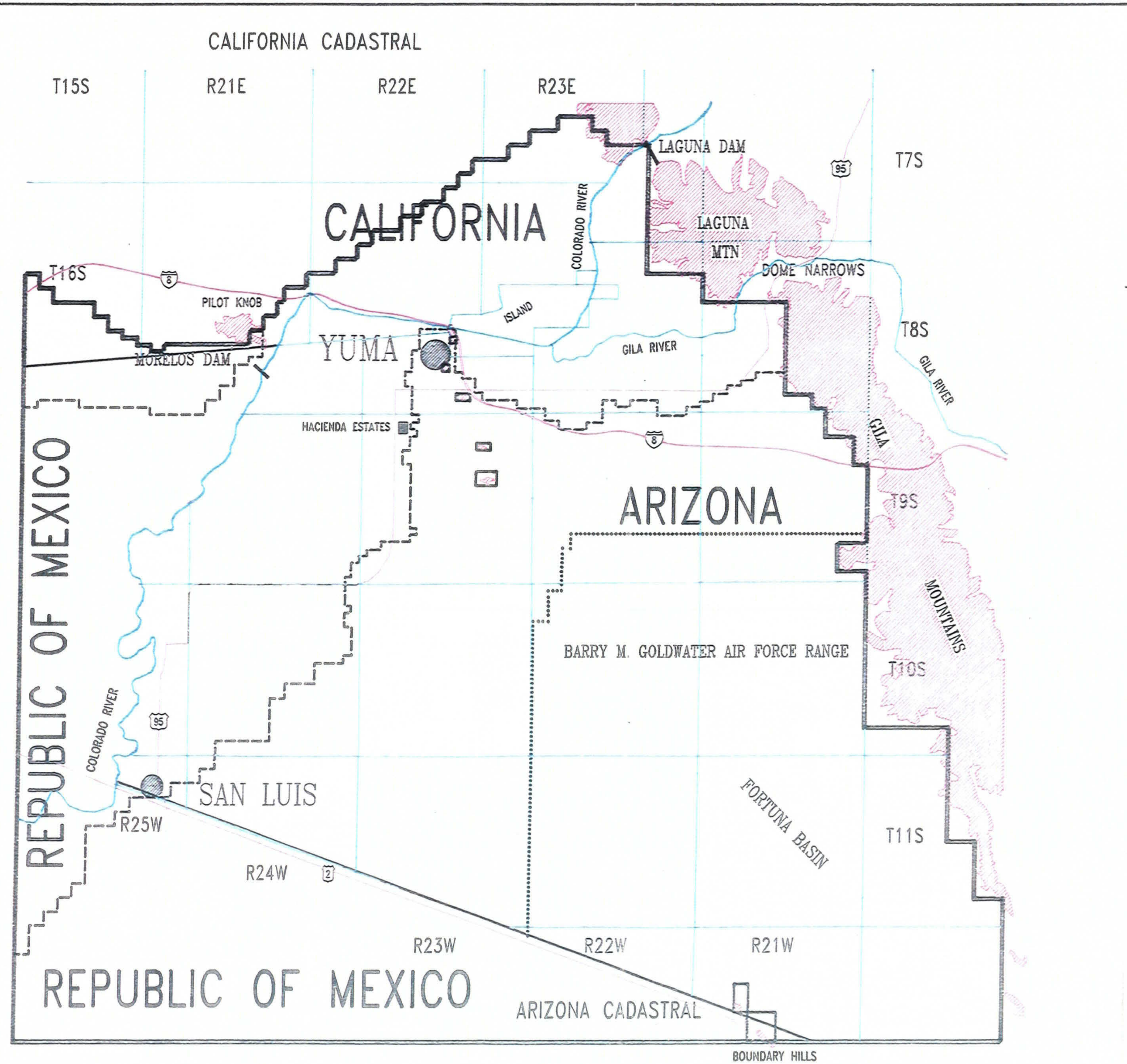
APPENDIX I FIGURES

FIGURE 1 AREA LOCATION ARIZONA, CALIFORNIA MEXICO



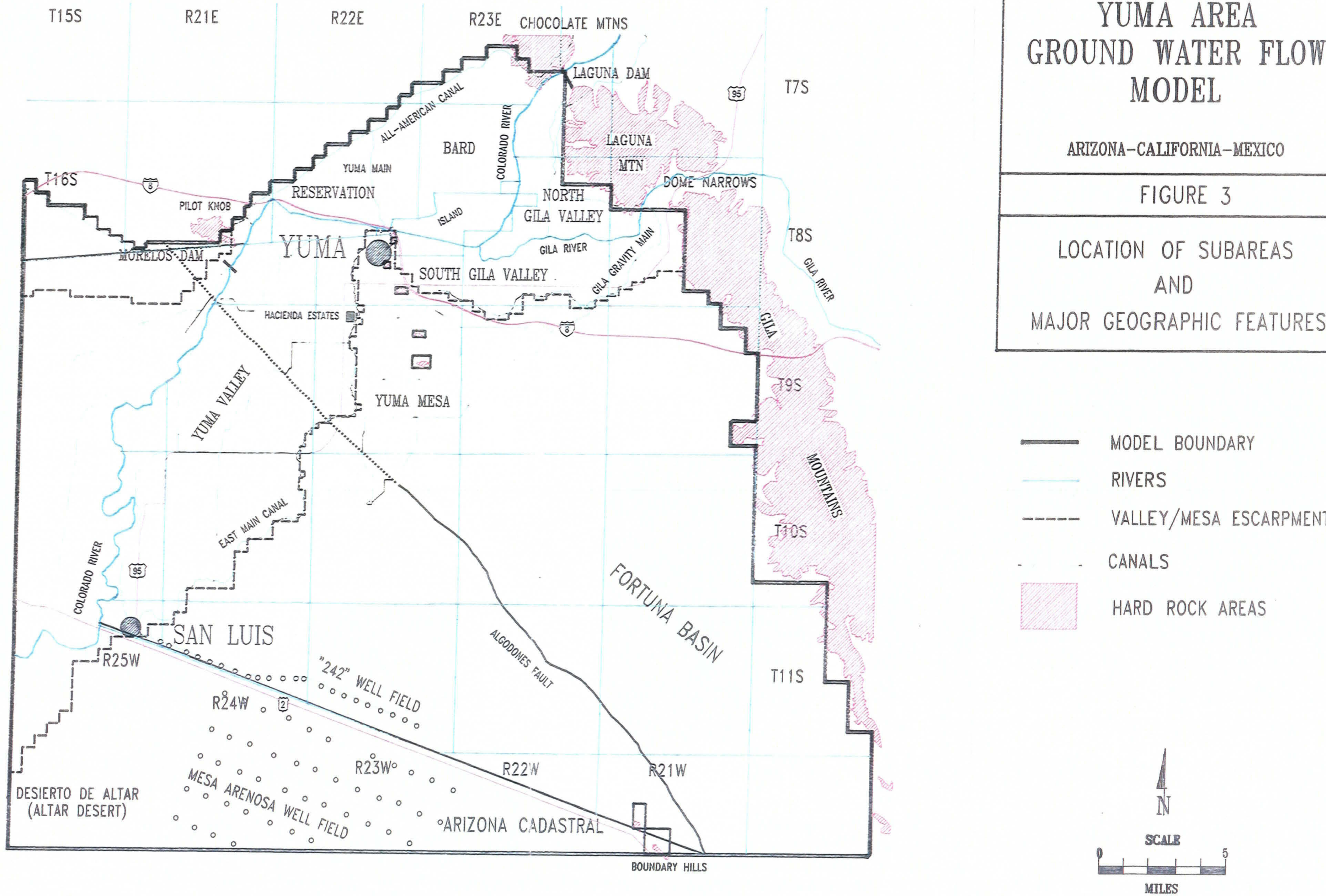
YUMA AREA GROUND WATER FLOW MODEL

ARIZONA–CALIFORNIA–MEXICO

FIGURE 2

Yuma Area

General Location

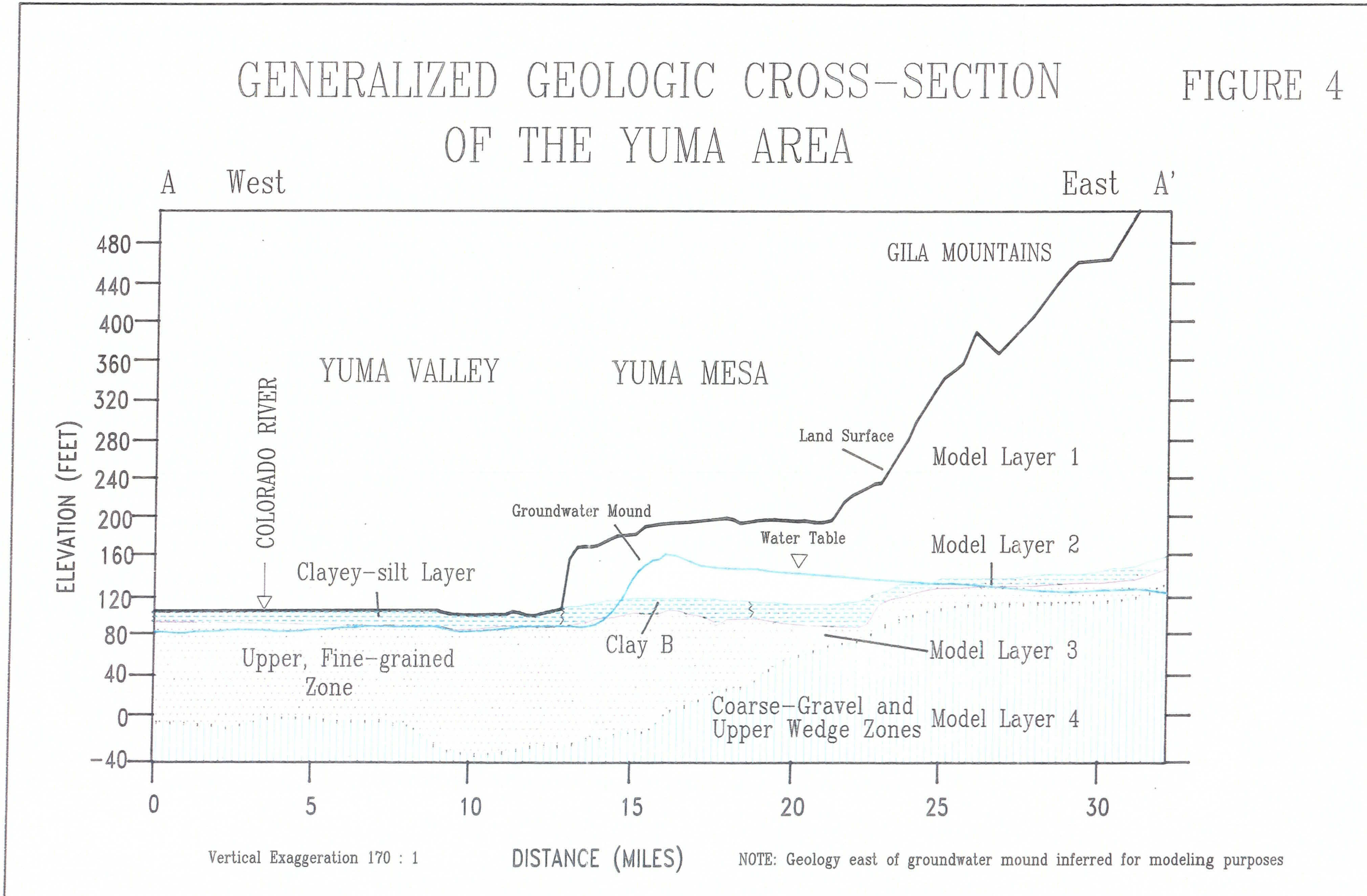


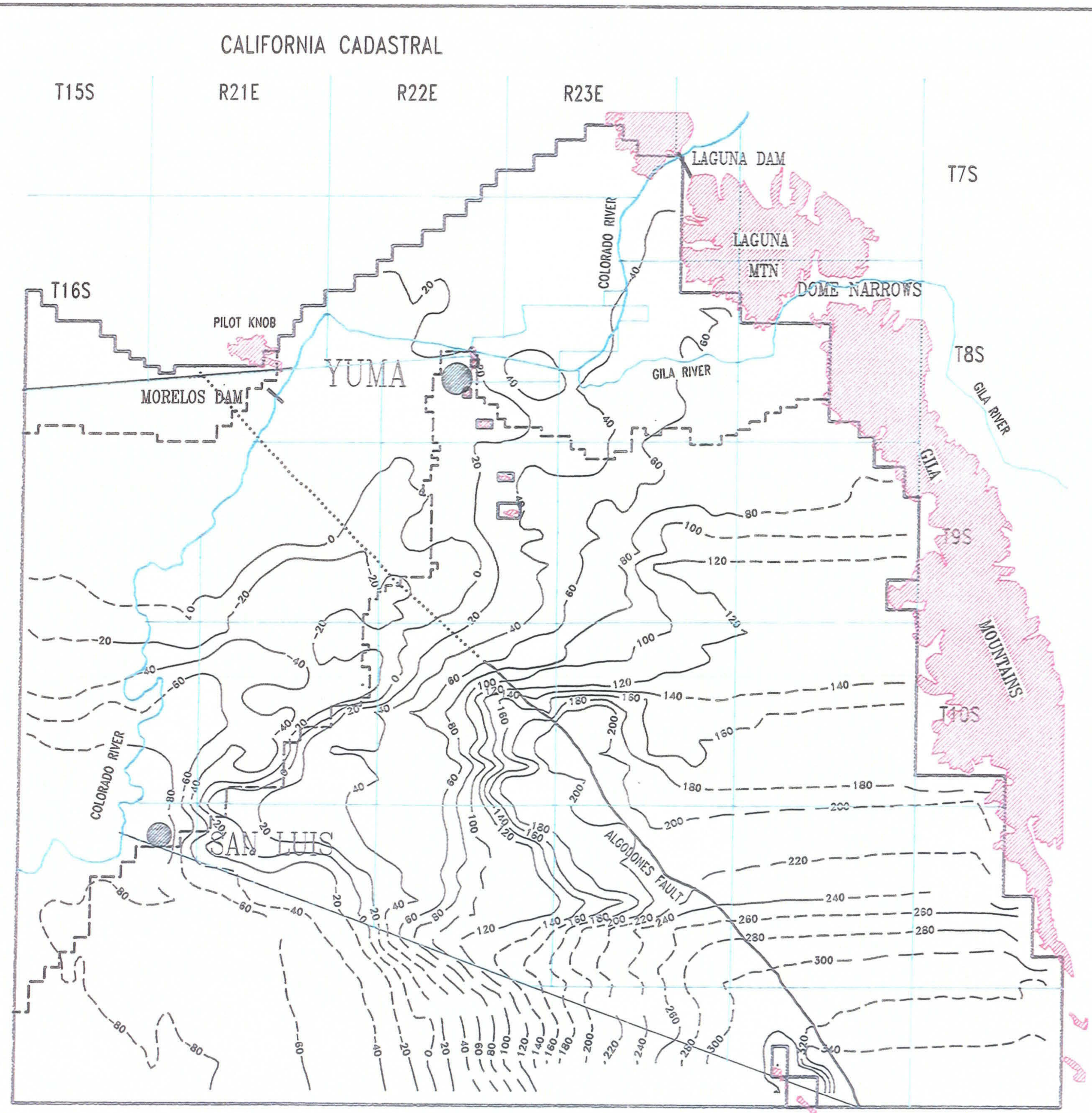
YUMA AREA GROUND WATER FLOW MODEL

ARIZONA-CALIFORNIA-MEXICO

FIGURE 3

LOCATION OF SUBAREAS AND MAJOR GEOGRAPHIC FEATURES


GENERALIZED GEOLOGIC CROSS-SECTION
OF THE YUMA AREA
FIGURE 4
A West
East A'
ELEVATION (FEET)
480
440
400
360
320
280
240
200
160
120
80
40
0
-40
GILA MOUNTAINS
YUMA VALLEY
YUMA MESA
COLORADO RIVER
Land Surface
Model Layer 1
Groundwater Mound
Water Table
Model Layer 2
Clayey-silt Layer
Clay B
Model Layer 3
Upper, Fine-grained
Zone
Coarse-Gravel and
Upper Wedge Zones
Model Layer 4
0
5
10
15
20
25
30
Vertical Exaggeration 170 : 1
DISTANCE (MILES)
NOTE: Geology east of groundwater mound inferred for modeling purposes



YUMA AREA GROUND WATER FLOW MODEL

ARIZONA–CALIFORNIA–MEXICO

FIGURE 5

COARSE–GRAVEL ZONE TOP ELEVATION CONTOURS (MODEL LAYER 4)

Units = Feet above MSL

HARD ROCK AREAS

MODEL BOUNDARY

RIVERS

VALLEY/MESA ESCARPMENT

COARSE GRAVEL LAYER TOP ELEVATION (DASHED WHERE INFERRED)

NOTE: No Data Available for Mexico and Fortuna Basin. Dashed Where Inferred for Modeling Purposes.

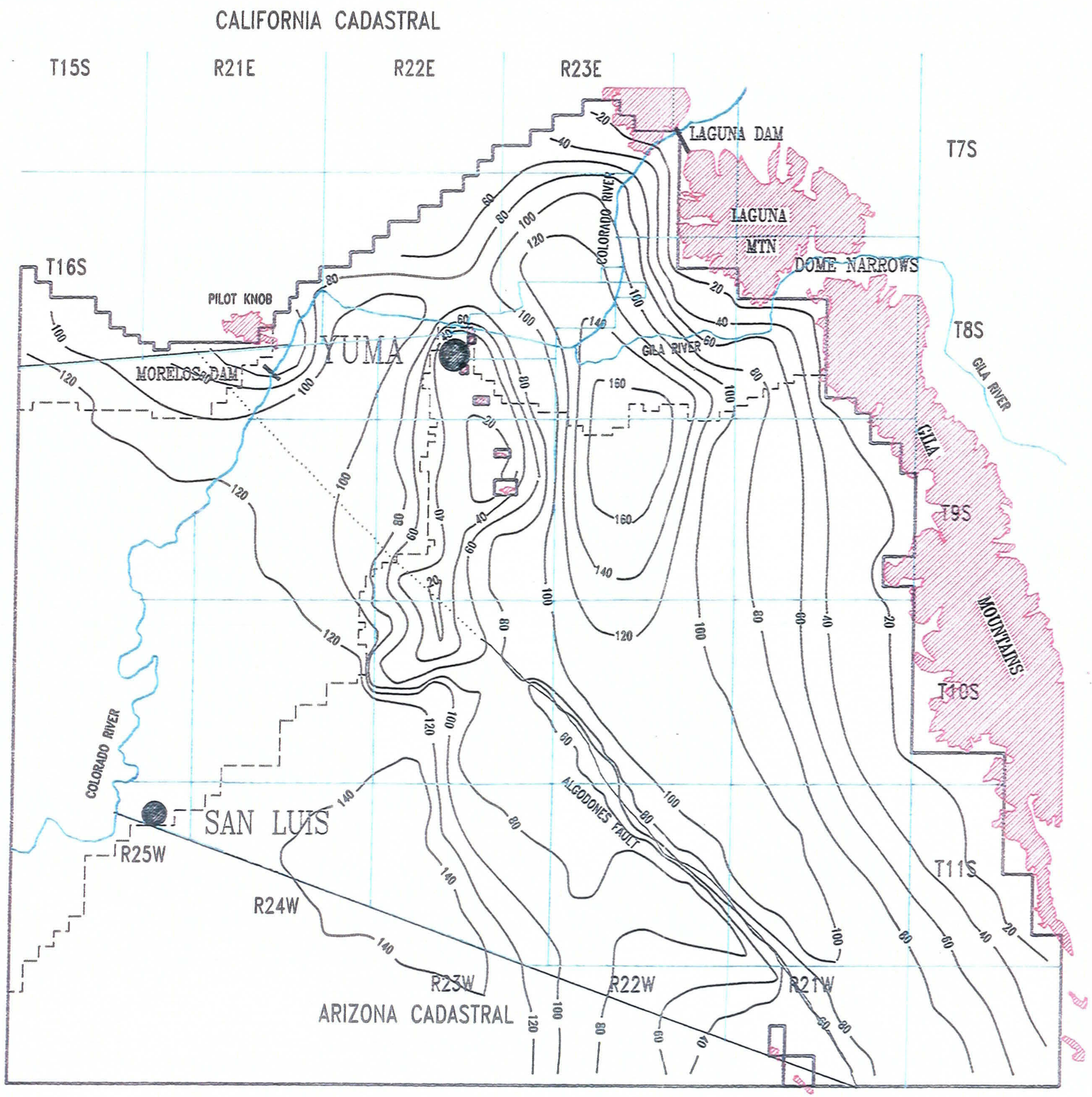
N

SCALE

0 5

MILES

Adopted From: Olmsted and Others, 1973



YUMA AREA GROUND WATER FLOW MODEL

ARIZONA-CALIFORNIA-MEXICO

FIGURE 6

TRANSMISSIVITY OF COARSE-GRAVEL AND UPPER WEDGE ZONES (MODEL LAYER 4)

Units = 1000s Feet-Squared/Day

HARD ROCK AREAS

MODEL BOUNDARY

RIVERS

VALLEY/MESA ESCARPMENT

EQUAL TRANSMISSIVITY CONTOURS

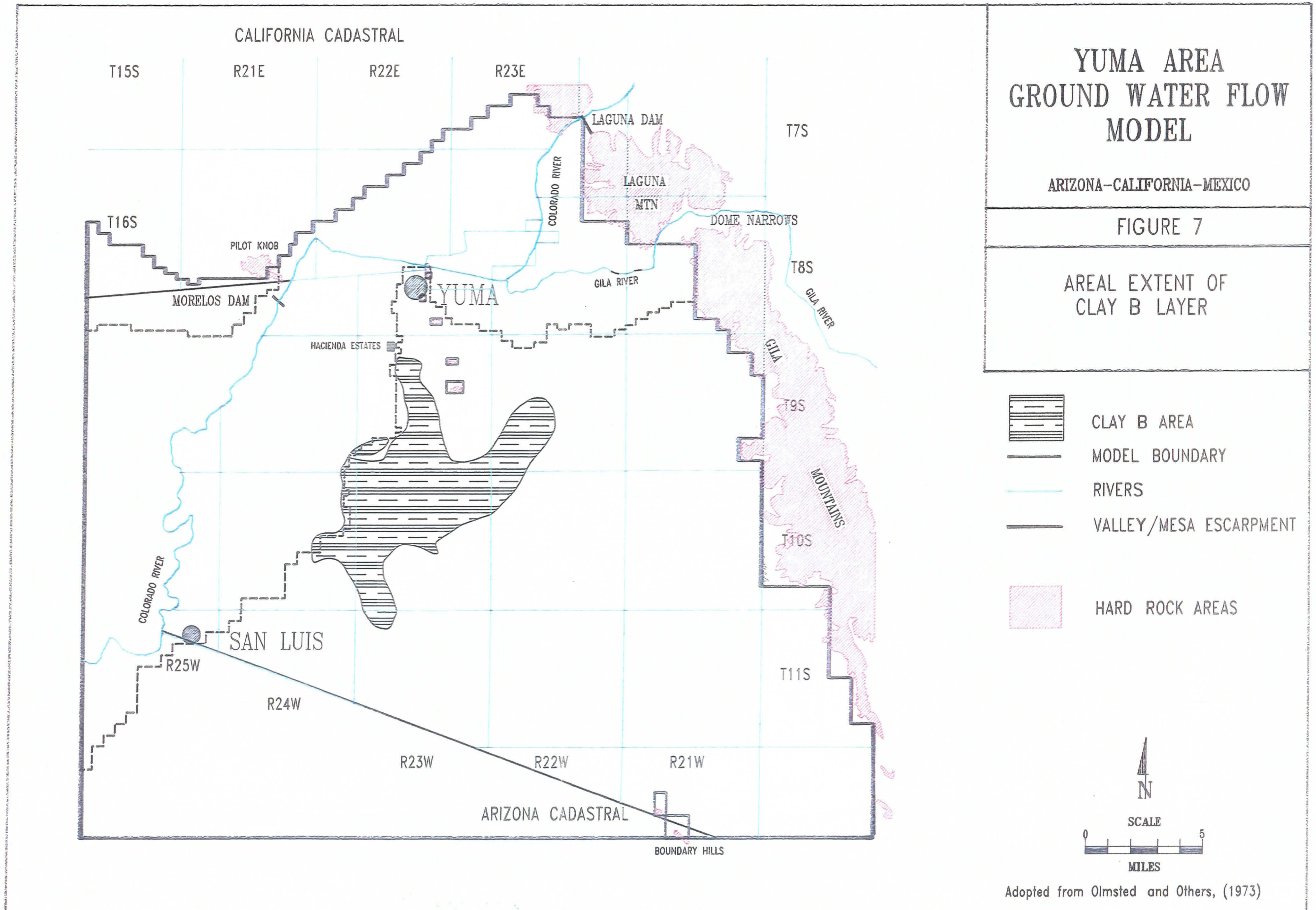
N

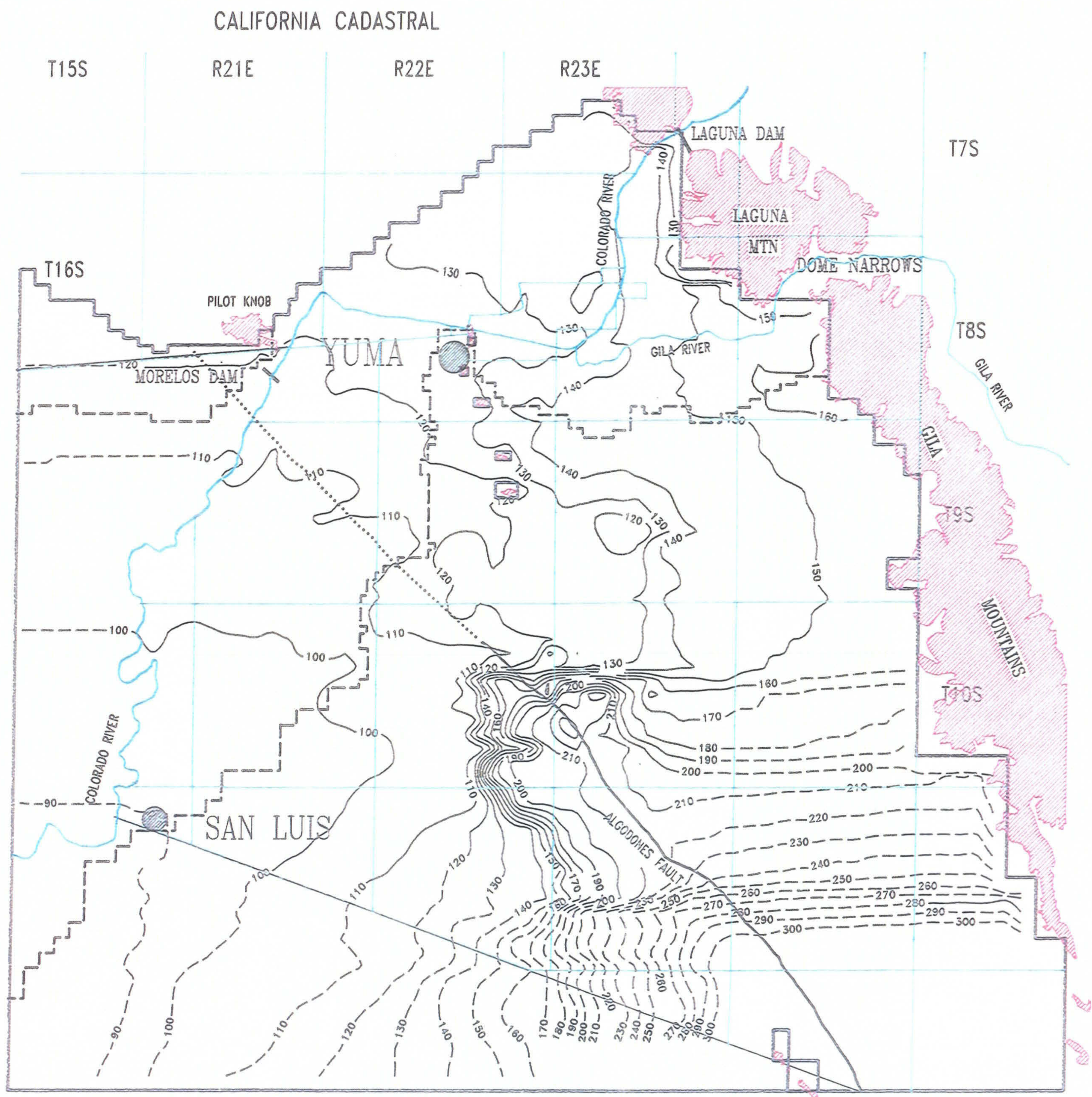
SCALE

0 5

MILES

Adopted From Olmsted and Others, (1973)


YUMA AREA
GROUND WATER FLOW
MODEL
ARIZONA-CALIFORNIA-MEXICO
FIGURE 7
AREAL EXTENT OF
CLAY B LAYER
CALIFORNIA CADASTRAL
T15S
R21E
R22E
R23E
T16S
T7S
T8S
T9S
T10S
T11S
LAGUNA DAM
LAGUNA
MTN
DOME NARROWS
COLORADO RIVER
GILA RIVER
GILA
MOUNTAINS
PILOT KNOB
MORELOS DAM
YUMA
HACIENDA ESTATES
SAN LUIS
R25W
R24W
R23W
R22W
R21W
ARIZONA CADASTRAL
BOUNDARY HILLS
CLAY B AREA
MODEL BOUNDARY
RIVERS
VALLEY/MESA ESCARPMENT
HARD ROCK AREAS
N
SCALE
0
5
MILES
Adopted from Olmsted and Others, (1973)



YUMA AREA GROUND WATER FLOW MODEL

ARIZONA-CALIFORNIA-MEXICO

FIGURE 8

CLAY B / RIVER VALLEY TOP ELEVATION CONTOURS (MODEL LAYER 2)

Units = Feet above MSL

HARD ROCK AREAS

MODEL BOUNDARY

RIVERS

VALLEY/MESA ESCARPMENT

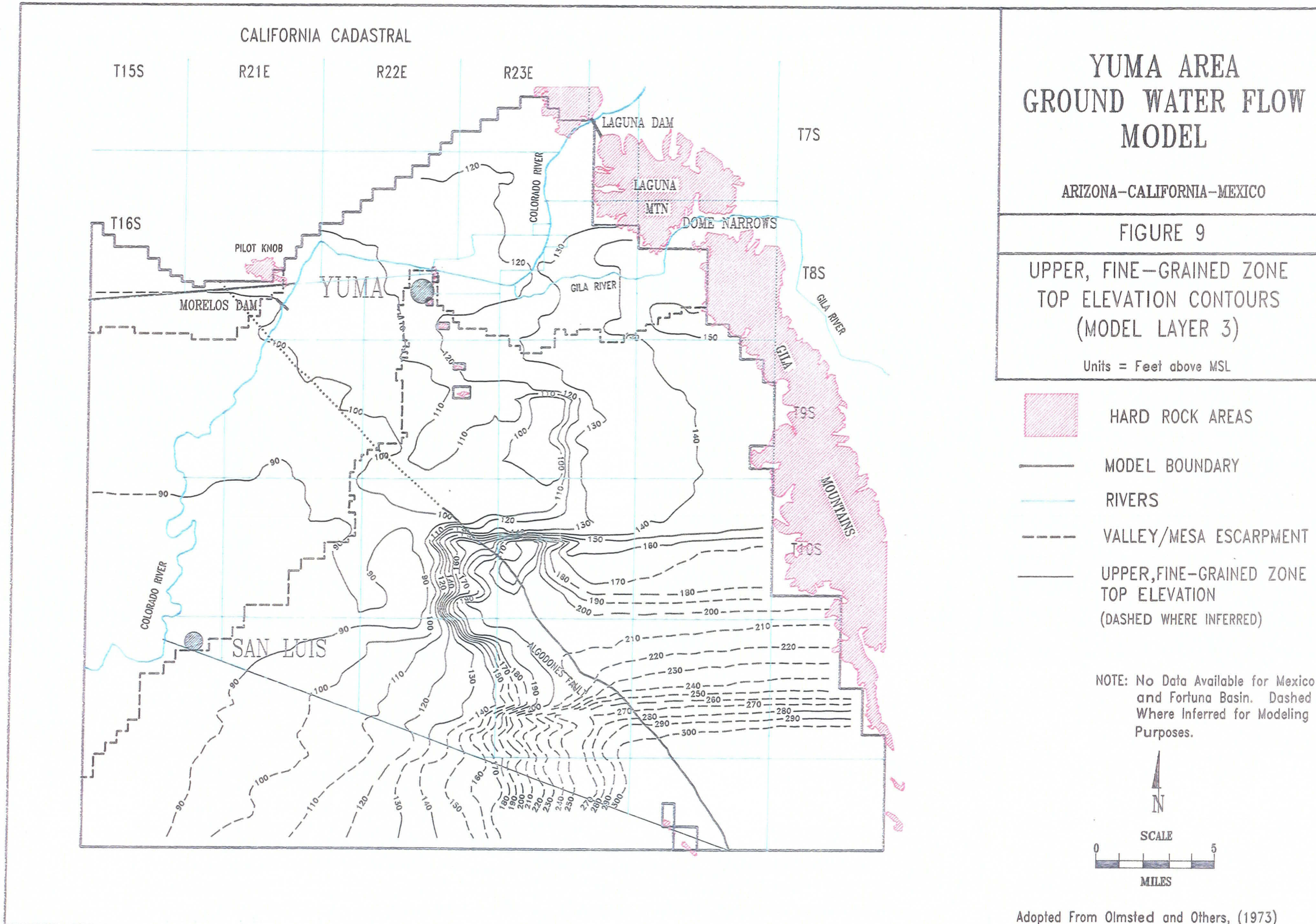
ELEVATION OF CLAY B/RIVER VALLEY TOP (DASHED WHERE INFERRED)

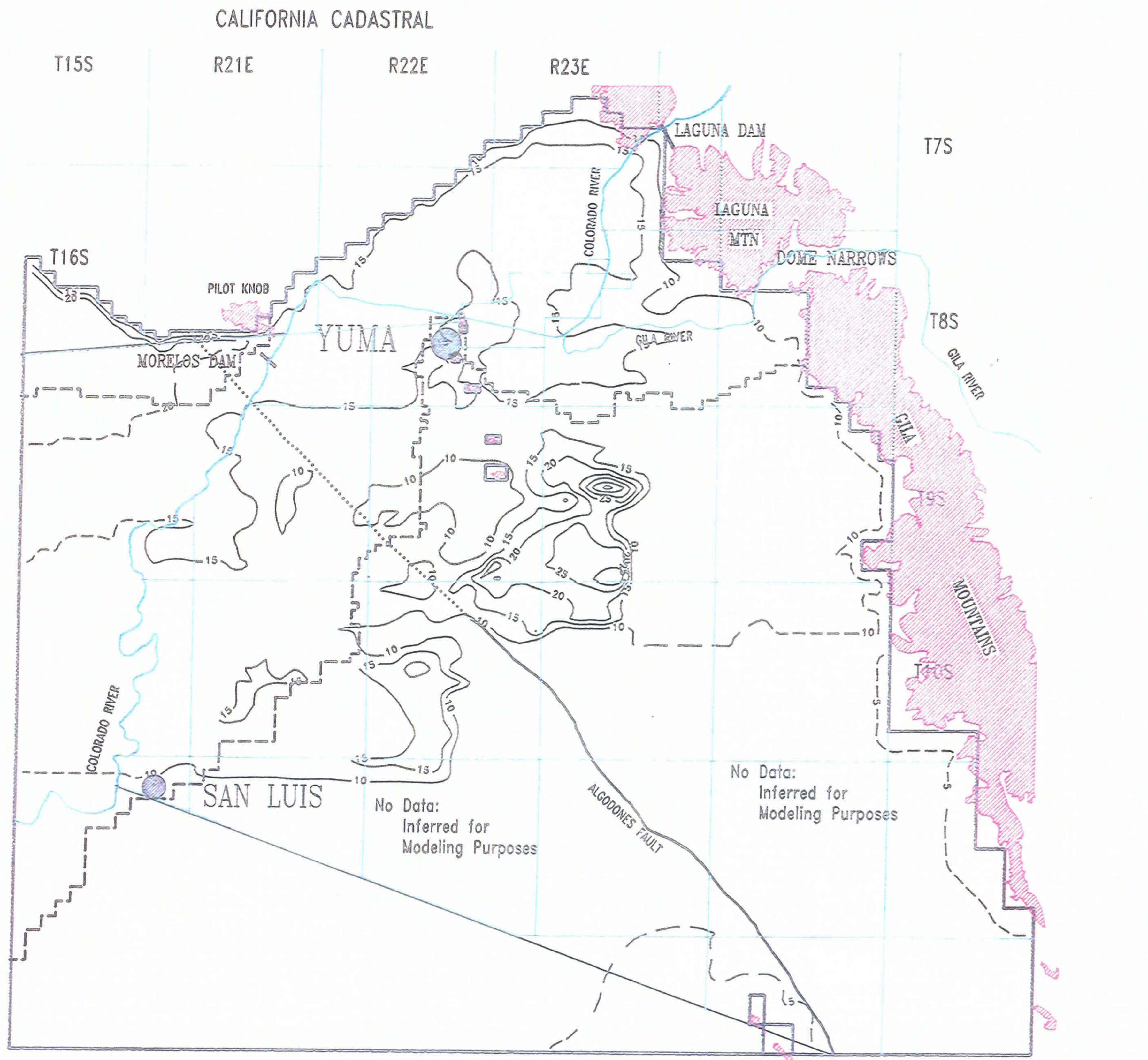
NOTE: No Data Available for Mexico and Fortuna Basin. Dashed Where Inferred for Modeling Purposes.

N

SCALE 0 5 MILES

Adopted From Olmsted and Others, (1973)


CALIFORNIA CADASTRAL
T15S
R21E
R22E
R23E
T16S
T7S
T8S
T9S
T10S
LAGUNA DAM
LAGUNA MTN
DOME NARROWS
COLORADO RIVER
GILA RIVER
PILOT KNOB
YUMA
MORELOS DAM
GILA MOUNTAINS
SAN LUIS
ALGODONES FAULT
YUMA AREA GROUND WATER FLOW MODEL
ARIZONA-CALIFORNIA-MEXICO
FIGURE 9
UPPER, FINE-GRAINED ZONE TOP ELEVATION CONTOURS (MODEL LAYER 3)
Units = Feet above MSL
HARD ROCK AREAS
MODEL BOUNDARY
RIVERS
VALLEY/MESA ESCARPMENT
UPPER, FINE-GRAINED ZONE TOP ELEVATION (DASHED WHERE INFERRED)
NOTE: No Data Available for Mexico and Fortuna Basin. Dashed Where Inferred for Modeling Purposes.
N
SCALE
0
5
MILES
Adopted From Olmsted and Others, (1973)



YUMA AREA GROUND WATER FLOW MODEL

ARIZONA-CALIFORNIA-MEXICO

FIGURE 10

ISOPACH MAP OF CLAY B AND CLAYEY-SILT IN RIVER VALLEY (MODEL LAYER 2)
Units = Feet

HARD ROCK AREAS

MODEL BOUNDARY

RIVERS

VALLEY/MESA ESCARPMENT

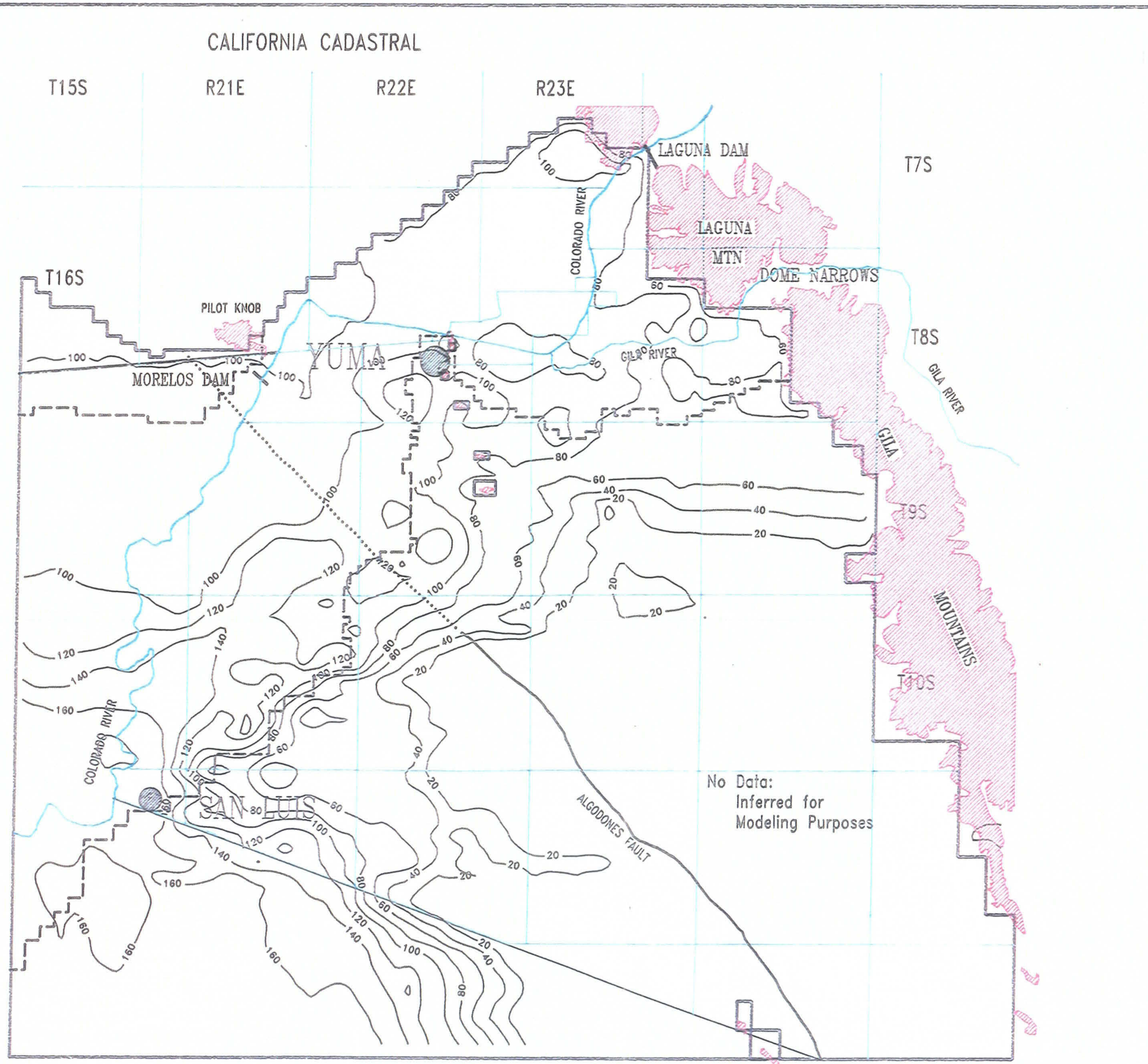
EQUAL THICKNESS CONTOURS

NOTE: No Data Available for Mexico and Fortuna Basin. Dashed Where Inferred for Modeling Purposes.

N

SCALE
0 5
MILES

Adopted From Olmsted and Others, (1973)



YUMA AREA GROUND WATER FLOW MODEL

ARIZONA–CALIFORNIA–MEXICO

FIGURE 11

ISOPACH MAP OF THE UPPER, FINE-GRAINED ZONE BELOW CLAY B (MODEL LAYER 3)

Units = Feet

HARD ROCK AREAS

MODEL BOUNDARY

RIVERS

VALLEY/MESA ESCARPMENT

EQUAL THICKNESS CONTOURS

NOTE: No Data Available for Mexico and Fortuna Basin. Dashed Where Inferred for Modeling Purposes.

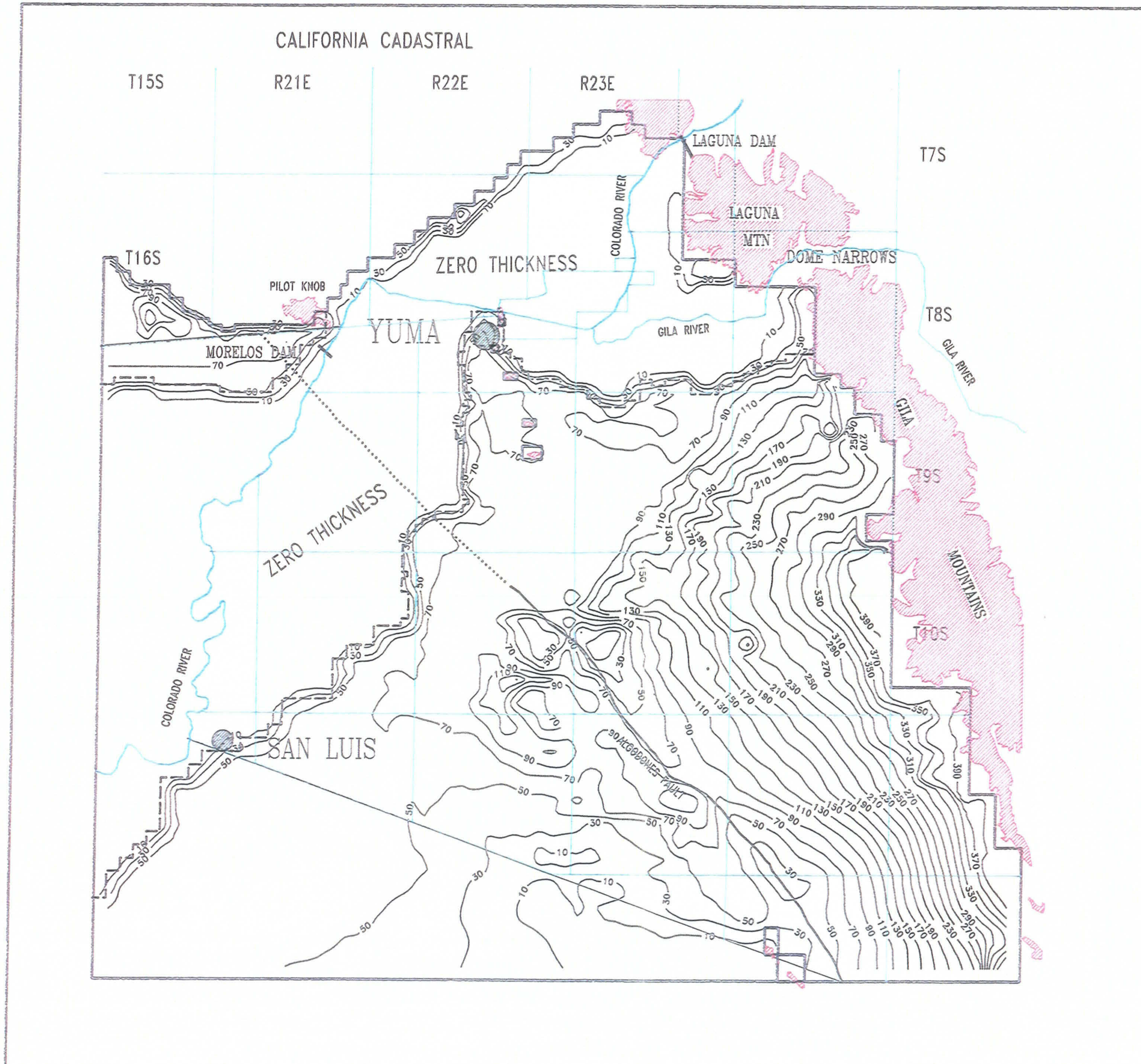
N

SCALE

0 5

MILES

Adopted From Olmsted and Others, (1973)



YUMA AREA GROUND WATER FLOW MODEL

ARIZONA-CALIFORNIA-MEXICO

FIGURE 12

ISOPACH MAP OF THE SEDIMENTS ABOVE CLAY B (MODEL LAYER 1)

Units = Feet

HARD ROCK AREAS

MODEL BOUNDARY

RIVERS

VALLEY/MESA ESCARPMENT

EQUAL THICKNESS CONTOURS

NOTE: No Data Available for Mexico and Fortuna Basin. Dashed Where Inferred for Modeling Purposes.

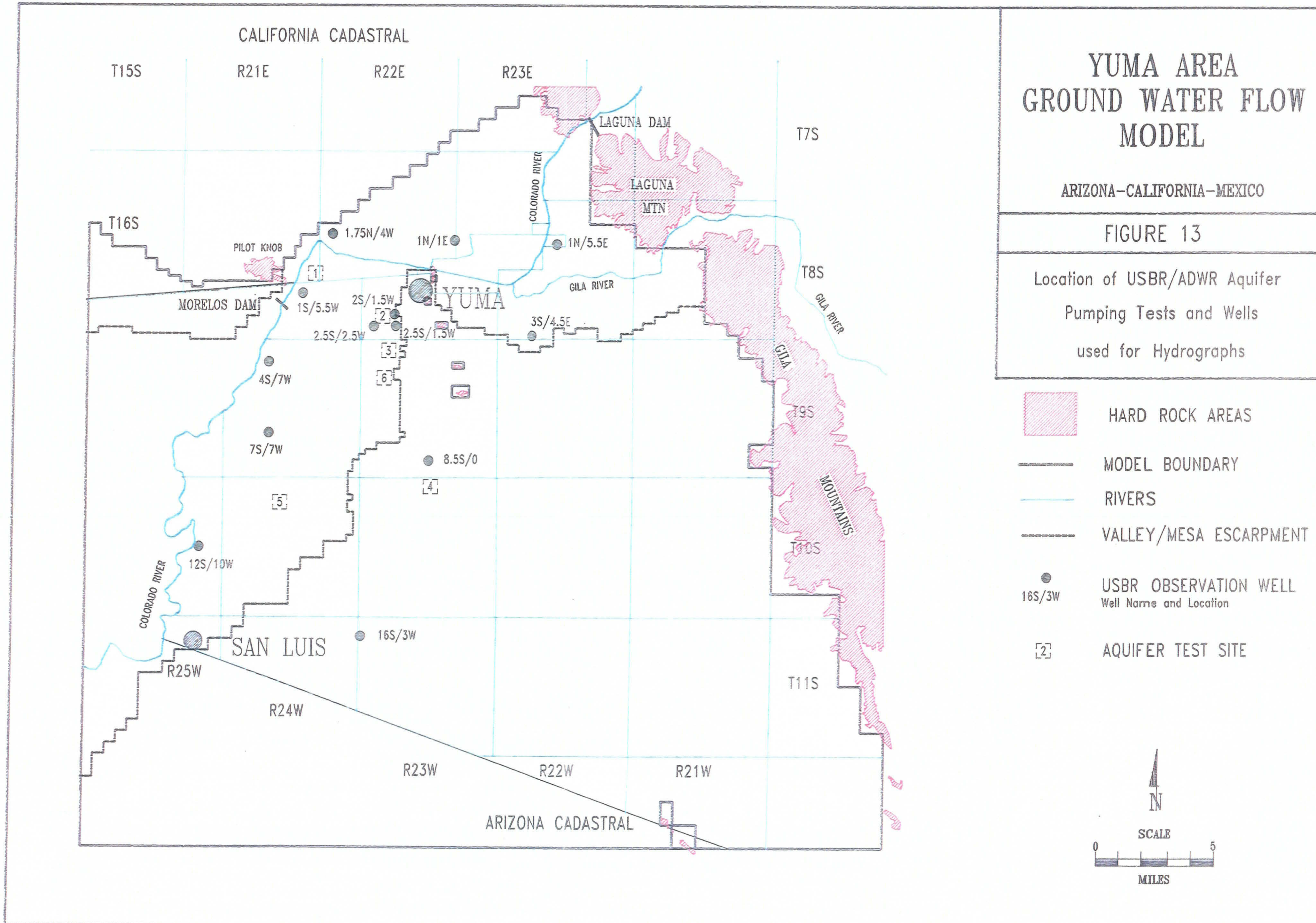
N

SCALE

0 5

MILES

Adopted From Olmsted and Others, (1973)

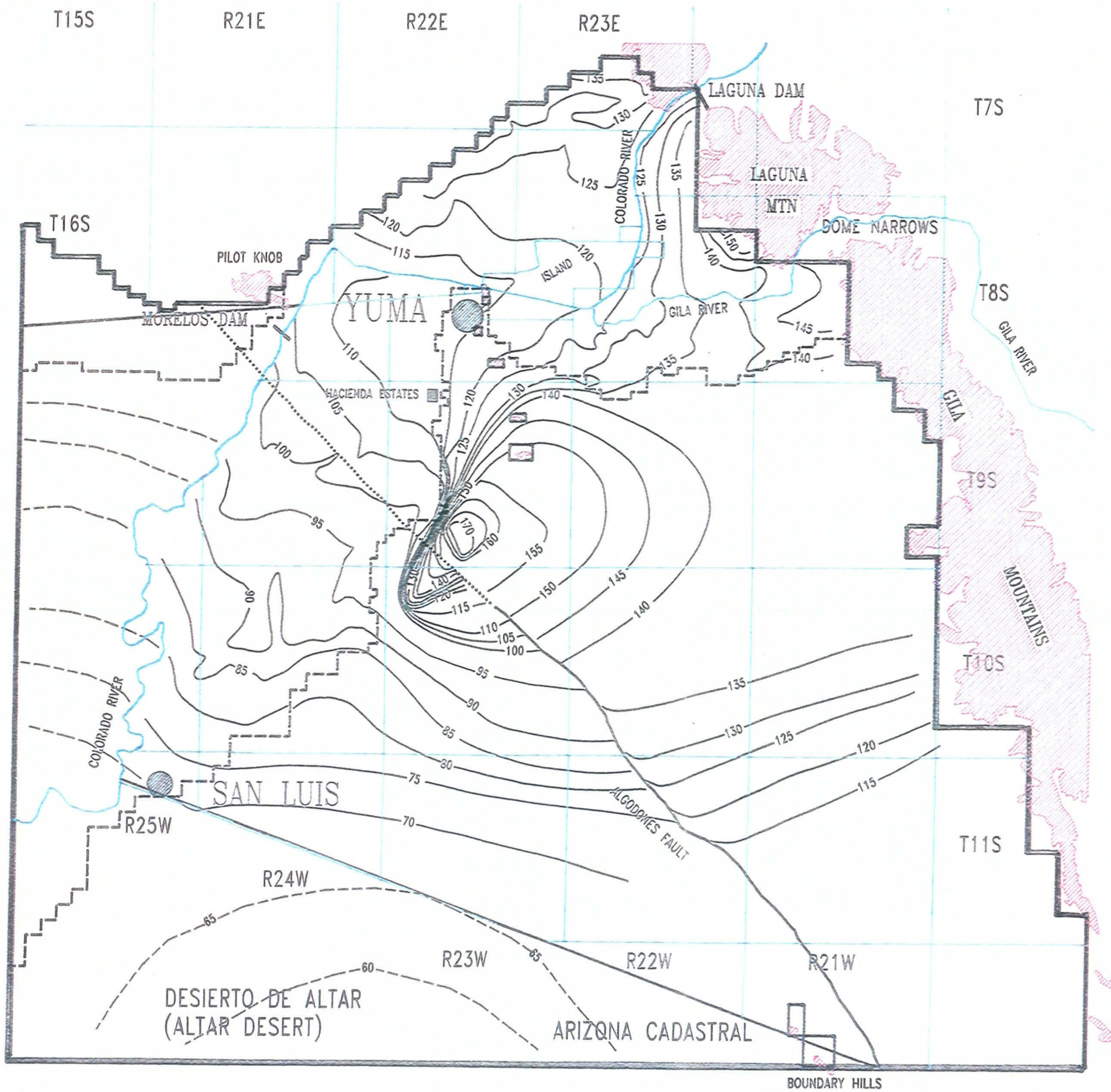


YUMA AREA GROUND WATER FLOW MODEL

ARIZONA-CALIFORNIA-MEXICO

FIGURE 13

Location of USBR/ADWR Aquifer Pumping Tests and Wells used for Hydrographs



YUMA AREA GROUND WATER FLOW MODEL

ARIZONA–CALIFORNIA–MEXICO

FIGURE 14

Measured Water Levels March 1978

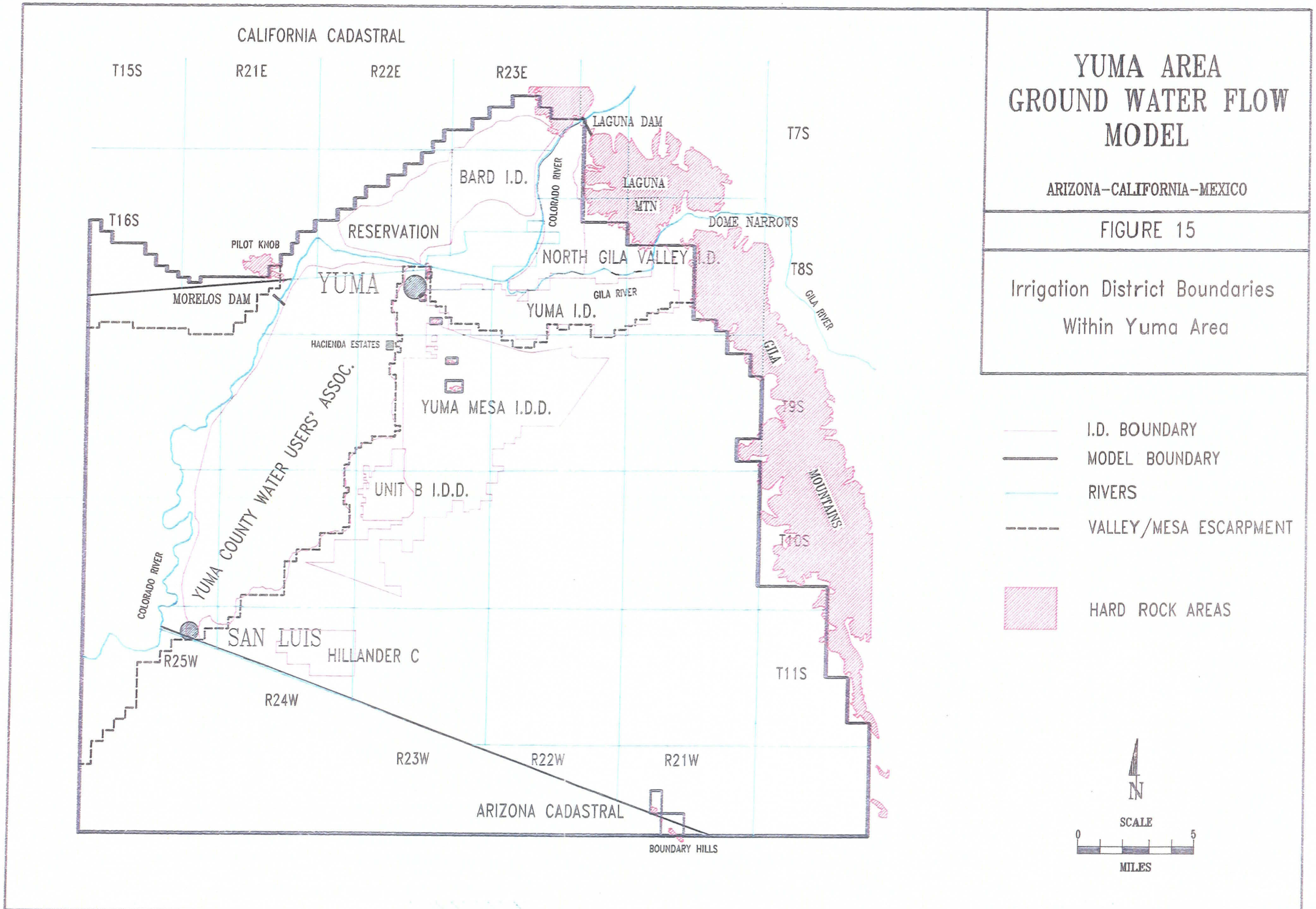
(Units = Feet above MSL)

- MEASURED WATER LEVELS (DASHED WHERE INFERRED)
- MODEL BOUNDARY
- RIVERS
- VALLEY/MESA ESCARPMENT
- HARD ROCK AREAS

NOTE: Adopted from USBR Yuma Area Ground Water Elevation Map. Mexico Water Levels are Approximated.

N

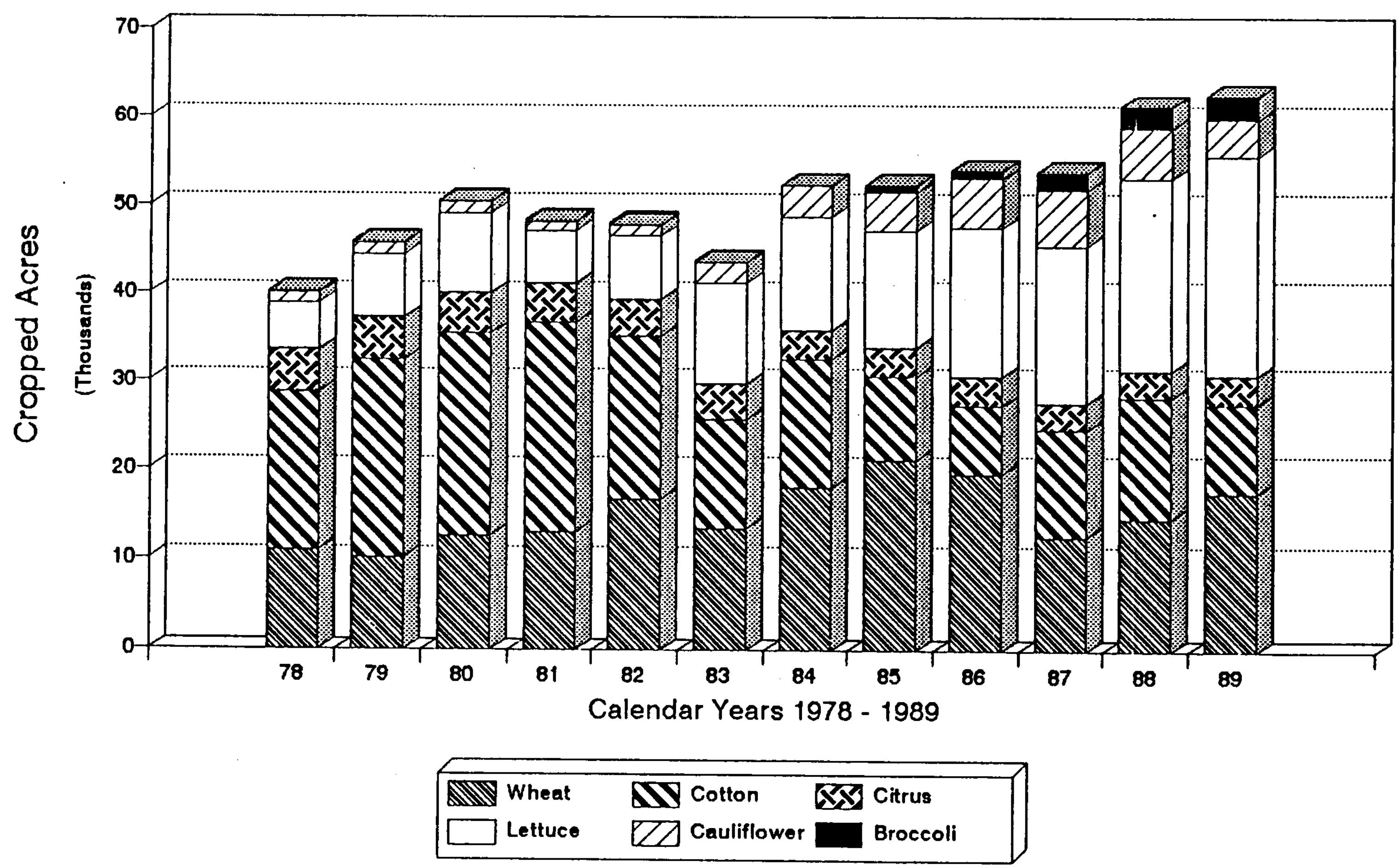
SCALE 0 5 MILES


YUMA AREA
GROUND WATER FLOW
MODEL
ARIZONA-CALIFORNIA-MEXICO
FIGURE 15
Irrigation District Boundaries
Within Yuma Area
I.D. BOUNDARY
MODEL BOUNDARY
RIVERS
VALLEY/MESA ESCARPMENT
HARD ROCK AREAS
N
SCALE
0
5
MILES
CALIFORNIA CADASTRAL
T15S
R21E
R22E
R23E
LAGUNA DAM
T7S
BARD I.D.
COLORADO RIVER
LAGUNA
MTN
DOME NARROWS
T16S
RESERVATION
PILOT KNOB
NORTH GILA VALLEY I.D.
T8S
YUMA
MORELOS DAM
GILA RIVER
YUMA I.D.
GILA RIVER
HACIENDA ESTATES
GILA
YUMA MESA I.D.D.
T9S
YUMA COUNTY WATER USERS' ASSOC.
UNIT B I.D.D.
MOUNTAINS
T10S
COLORADO RIVER
SAN LUIS
HILLANDER C
R25W
T11S
R24W
R23W
R22W
R21W
ARIZONA CADASTRAL
BOUNDARY HILLS

TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE YUMA VALLEY SUBAREA

Figure 16

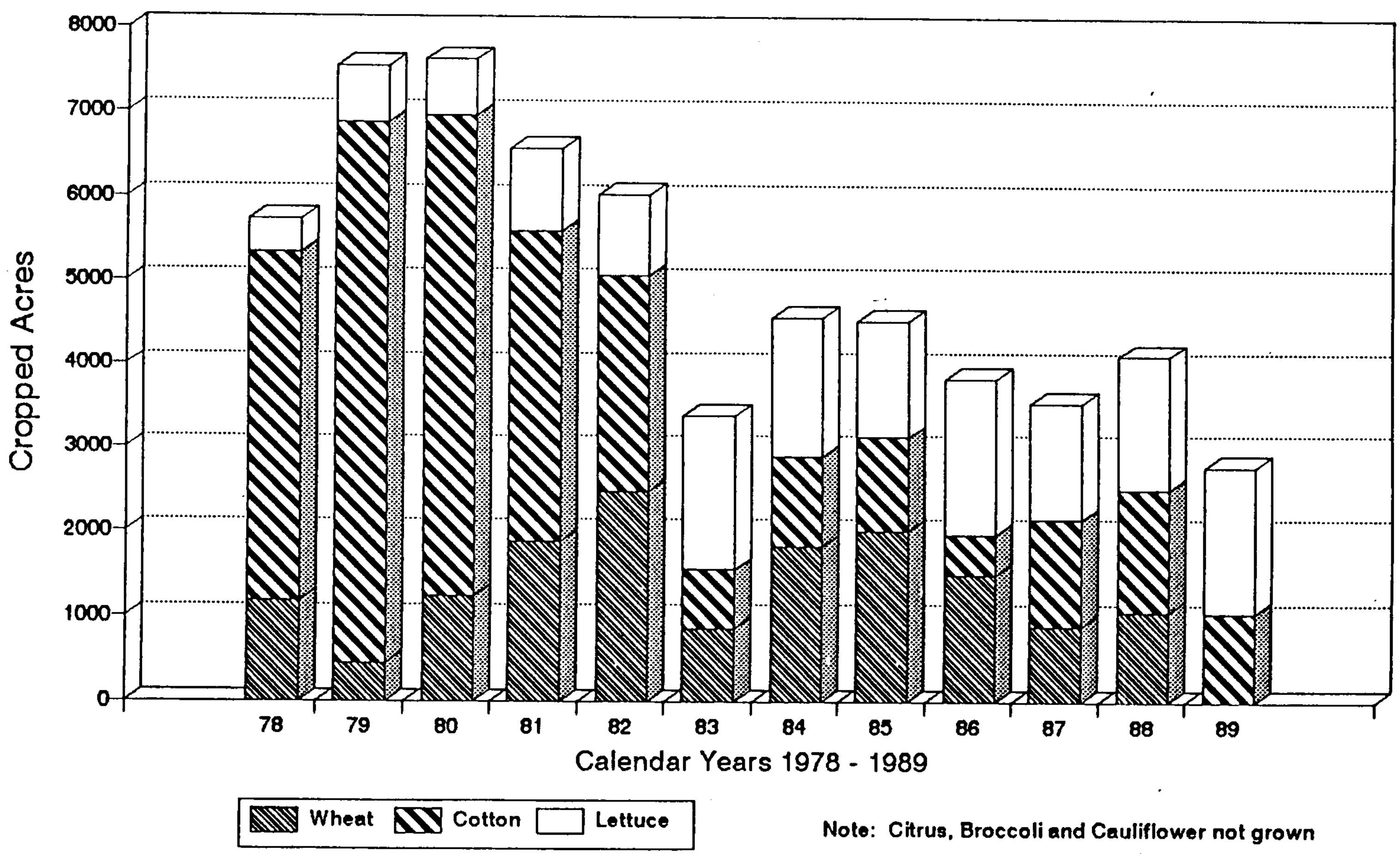
Yuma County Water Users Association



TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE RESERVATION SUBAREA

Figure 17

Reservation Irrigation District

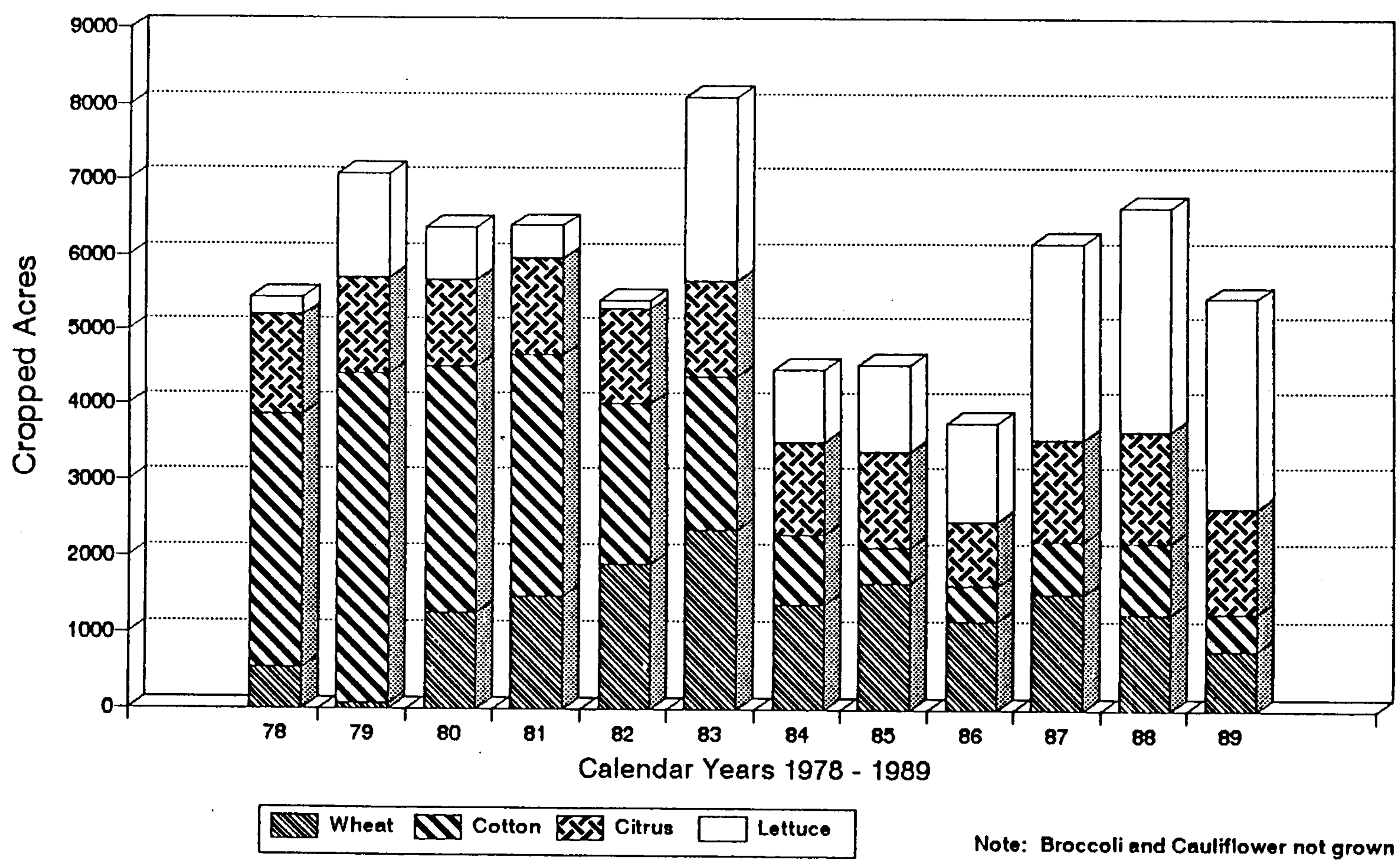


Note: Citrus, Broccoli and Cauliflower not grown

TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE RESERVATION SUBAREA

Figure 18

Bard Irrigation District

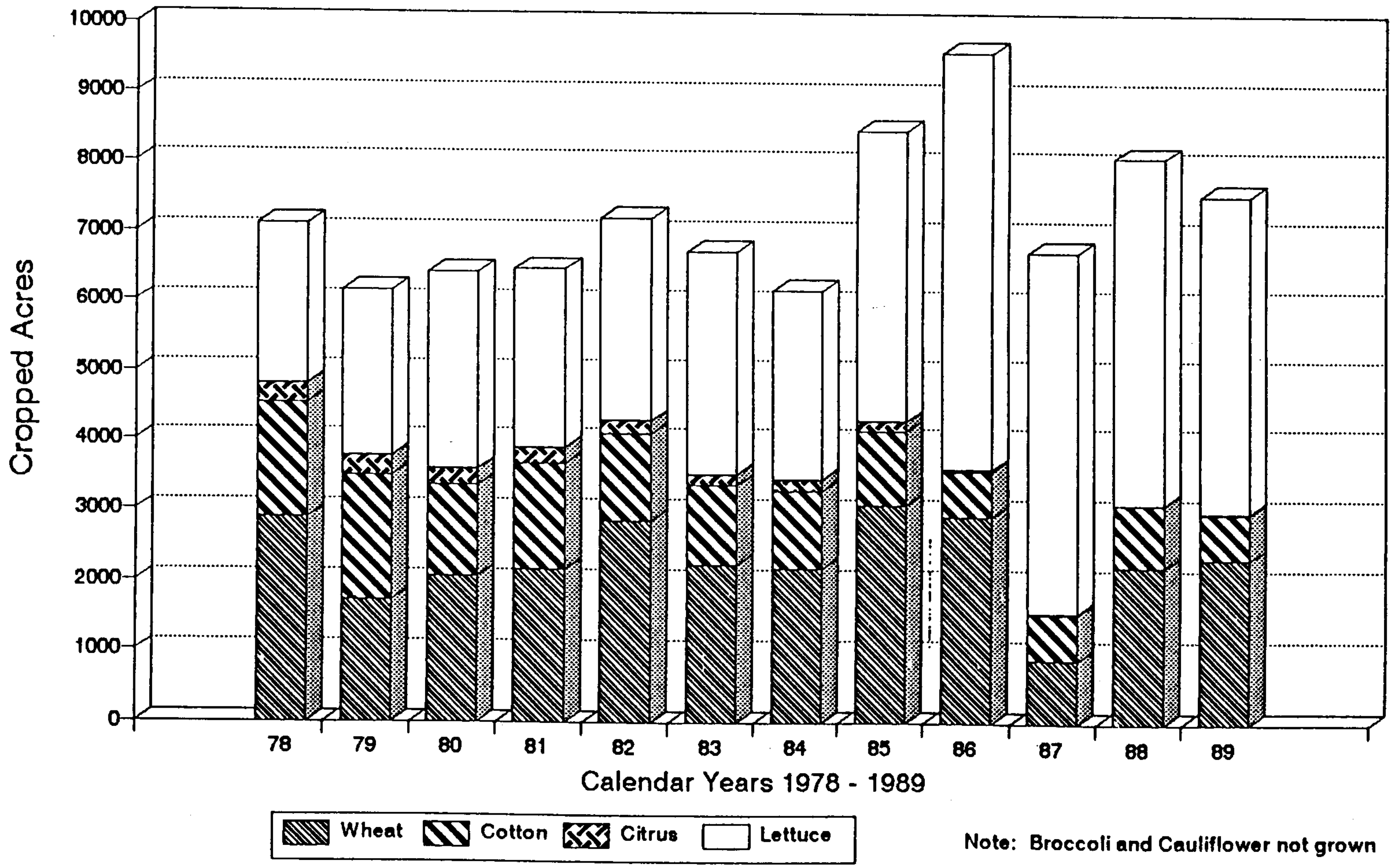


Note: Broccoli and Cauliflower not grown

Figure 19

TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE NORTH GILA VALLEY SUBAREA

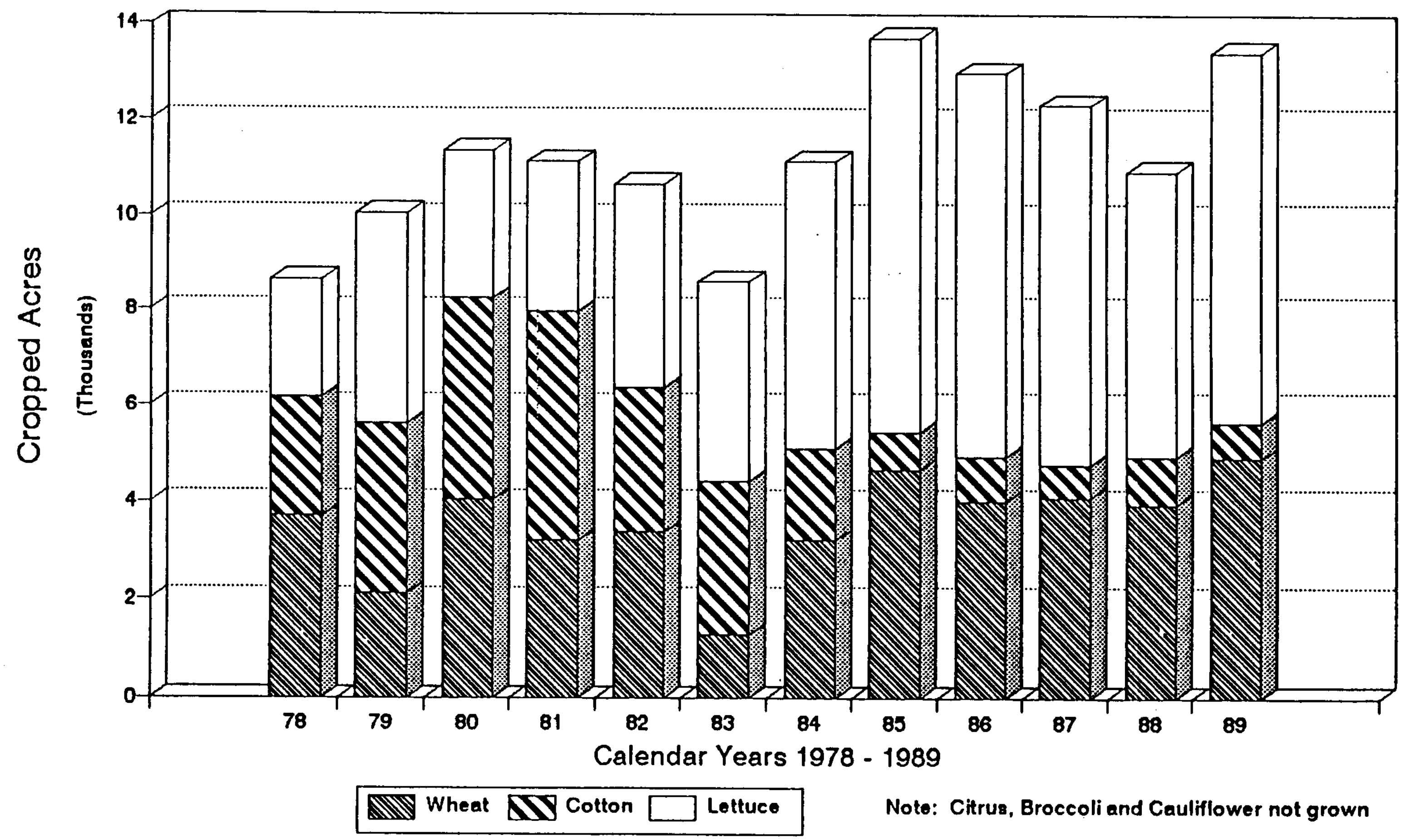
North Gila Valley Irrigation District



TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE SOUTH GILA VALLEY SUBAREA

Figure 20

Yuma Irrigation District

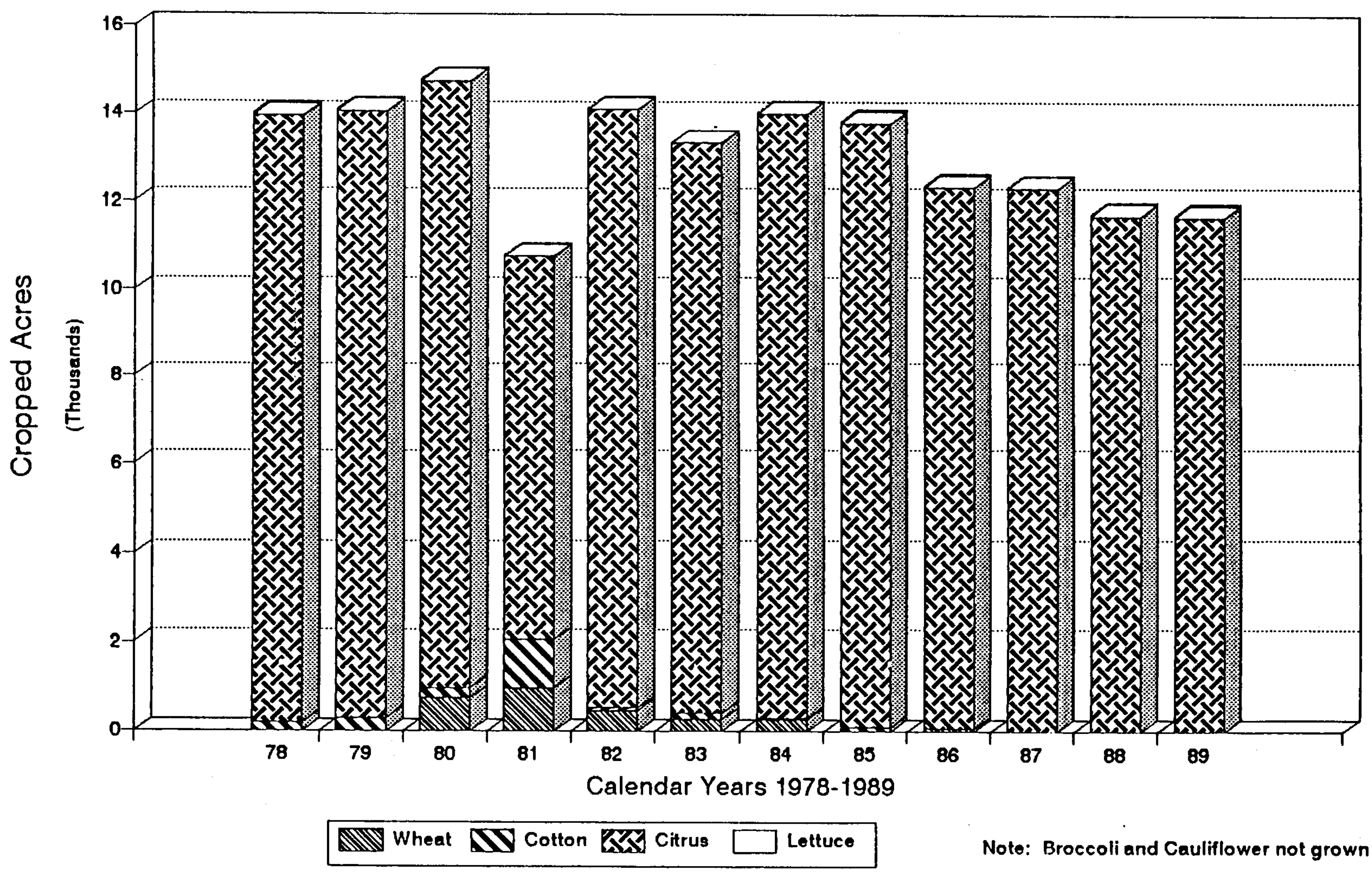


Note: Citrus, Broccoli and Cauliflower not grown

TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE YUMA MESA SUBAREA

Figure 21

Yuma Mesa Irrigation District

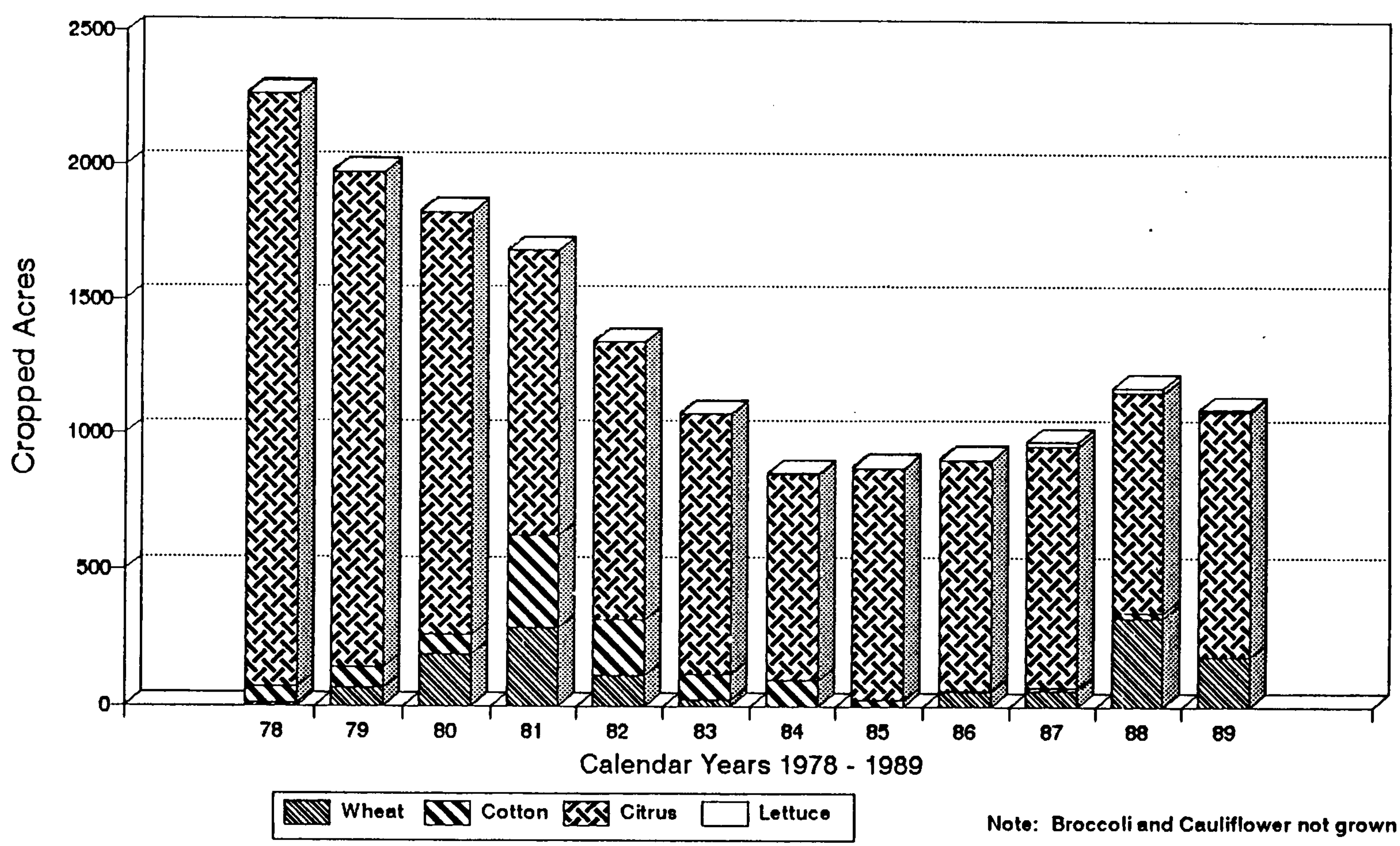


Note: Broccoli and Cauliflower not grown

Figure 22

TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE YUMA MESA SUBAREA

Unit B.I.D.D.

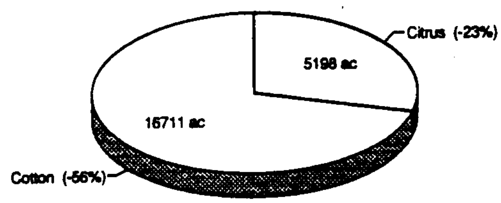


Note: Broccoli and Cauliflower not grown

PERCENT DECREASE AND INCREASE IN TOTAL ACRES FOR SELECTED CROPS BETWEEN 1978 AND 1989 FOR ALL IRRIGATION DISTRICTS

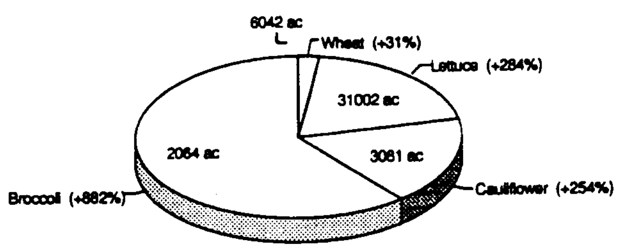
FIGURE 23

PERCENT DECREASE IN TOTAL ACRES FOR SELECTED CROPS BETWEEN 1978 AND 1989 FOR ALL IRRIGATION DISTRICTS IN THE YUMA AREA *USA ONLY*

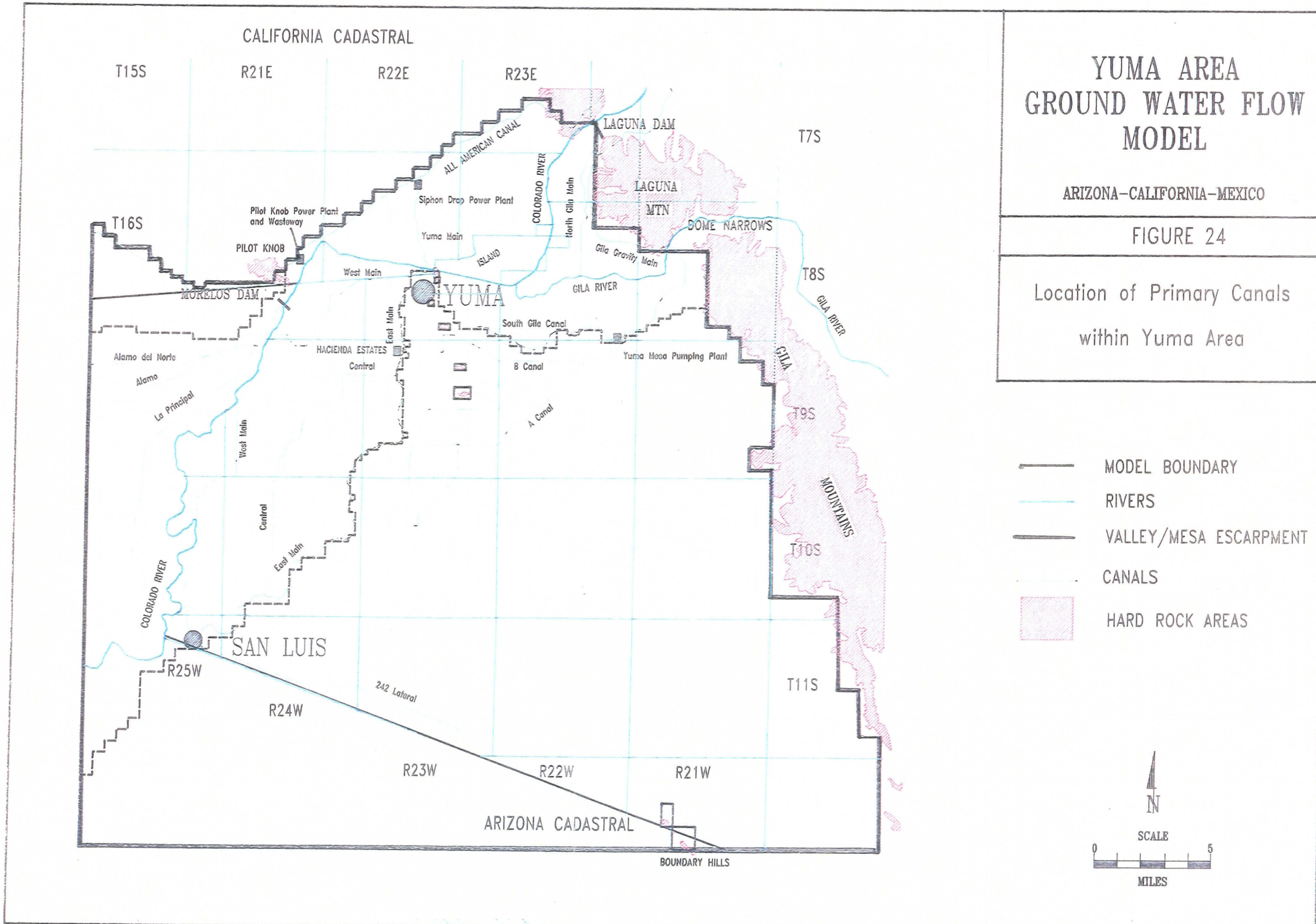


Note: -56% = % decrease in cropped acres between 1978 and 1989
16711 = total cropped acre decrease

PERCENT INCREASE IN TOTAL ACRES FOR SELECTED CROPS BETWEEN 1978 AND 1989 FOR ALL IRRIGATION DISTRICTS IN THE YUMA AREA *USA ONLY*



Note: +882% = % increase in cropped acres between 1979 and 1989
2064 = total cropped acre increase

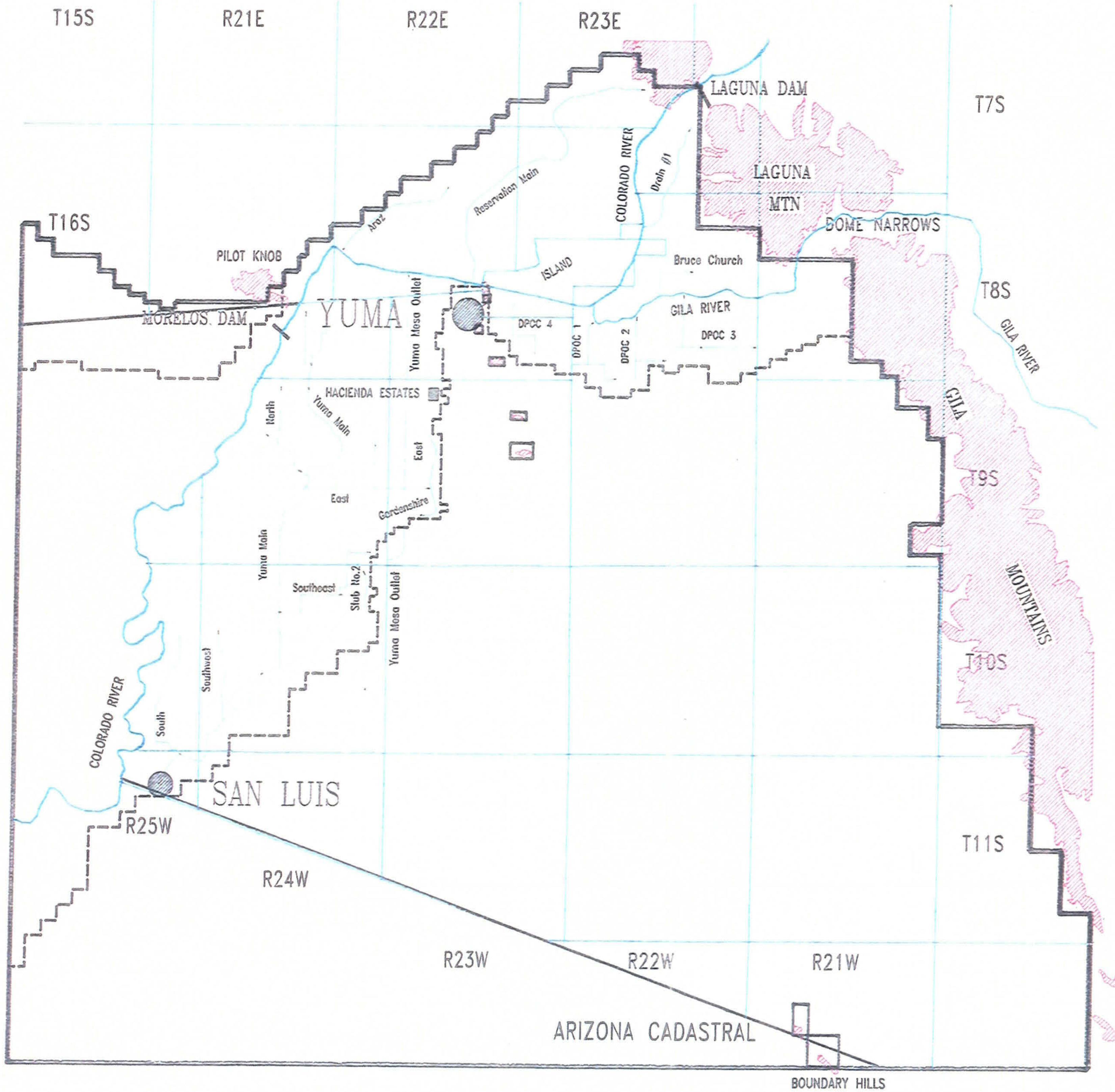


YUMA AREA GROUND WATER FLOW MODEL

ARIZONA-CALIFORNIA-MEXICO

FIGURE 24

Location of Primary Canals within Yuma Area



YUMA AREA GROUND WATER FLOW MODEL

ARIZONA-CALIFORNIA-MEXICO

FIGURE 25

Location of Primary Drains within Yuma Area

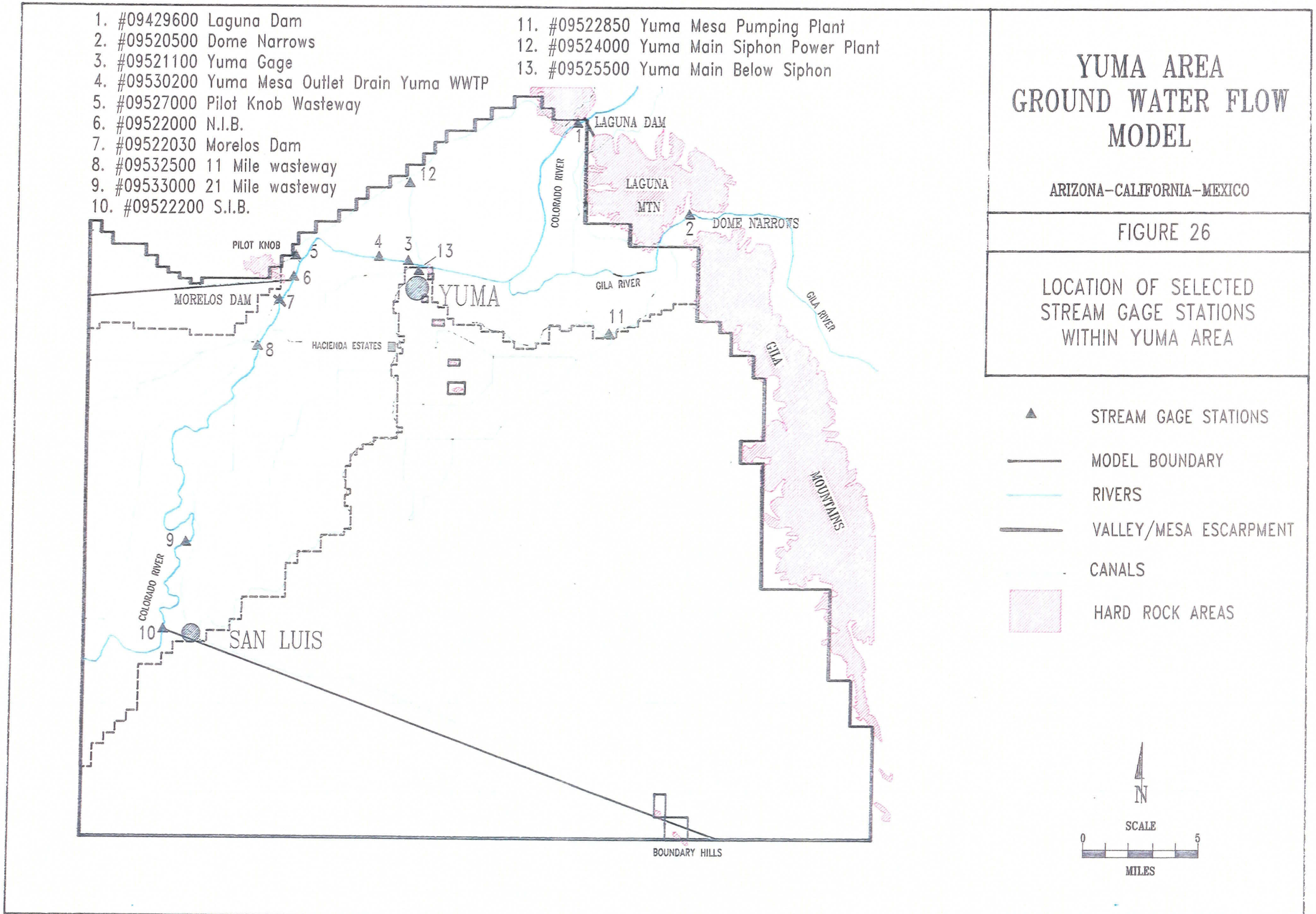

1. #09429600 Laguna Dam
2. #09520500 Dome Narrows
3. #09521100 Yuma Gage
4. #09530200 Yuma Mesa Outlet Drain Yuma WWTP
5. #09527000 Pilot Knob Wasteway
6. #09522000 N.I.B.
7. #09522030 Morelos Dam
8. #09532500 11 Mile wasteway
9. #09533000 21 Mile wasteway
10. #09522200 S.I.B.
11. #09522850 Yuma Mesa Pumping Plant
12. #09524000 Yuma Main Siphon Power Plant
13. #09525500 Yuma Main Below Siphon
YUMA AREA GROUND WATER FLOW MODEL
ARIZONA-CALIFORNIA-MEXICO
FIGURE 26
LOCATION OF SELECTED STREAM GAGE STATIONS WITHIN YUMA AREA
STREAM GAGE STATIONS
MODEL BOUNDARY
RIVERS
VALLEY/MESA ESCARPMENT
CANALS
HARD ROCK AREAS
LAGUNA DAM
LAGUNA MTN
DOME NARROWS
COLORADO RIVER
GILA RIVER
GILA MOUNTAINS
PILOT KNOB
MORELOS DAM
YUMA
HACIENDA ESTATES
SAN LUIS
BOUNDARY HILLS
N
SCALE
0
5
MILES

FIGURE 27. FLOW IN COLORADO RIVER AT LAGUNA DAM (Gage 09429600)

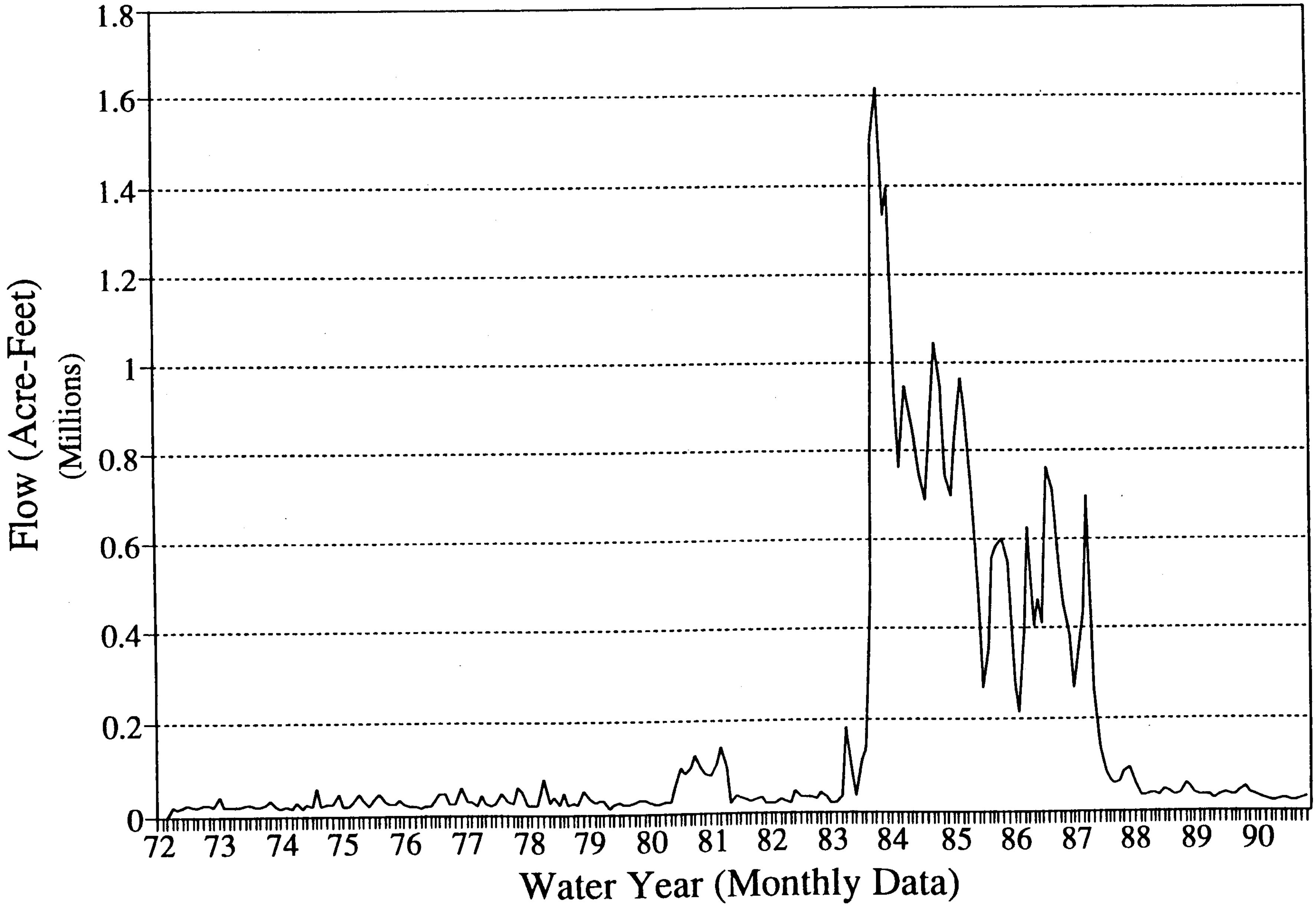
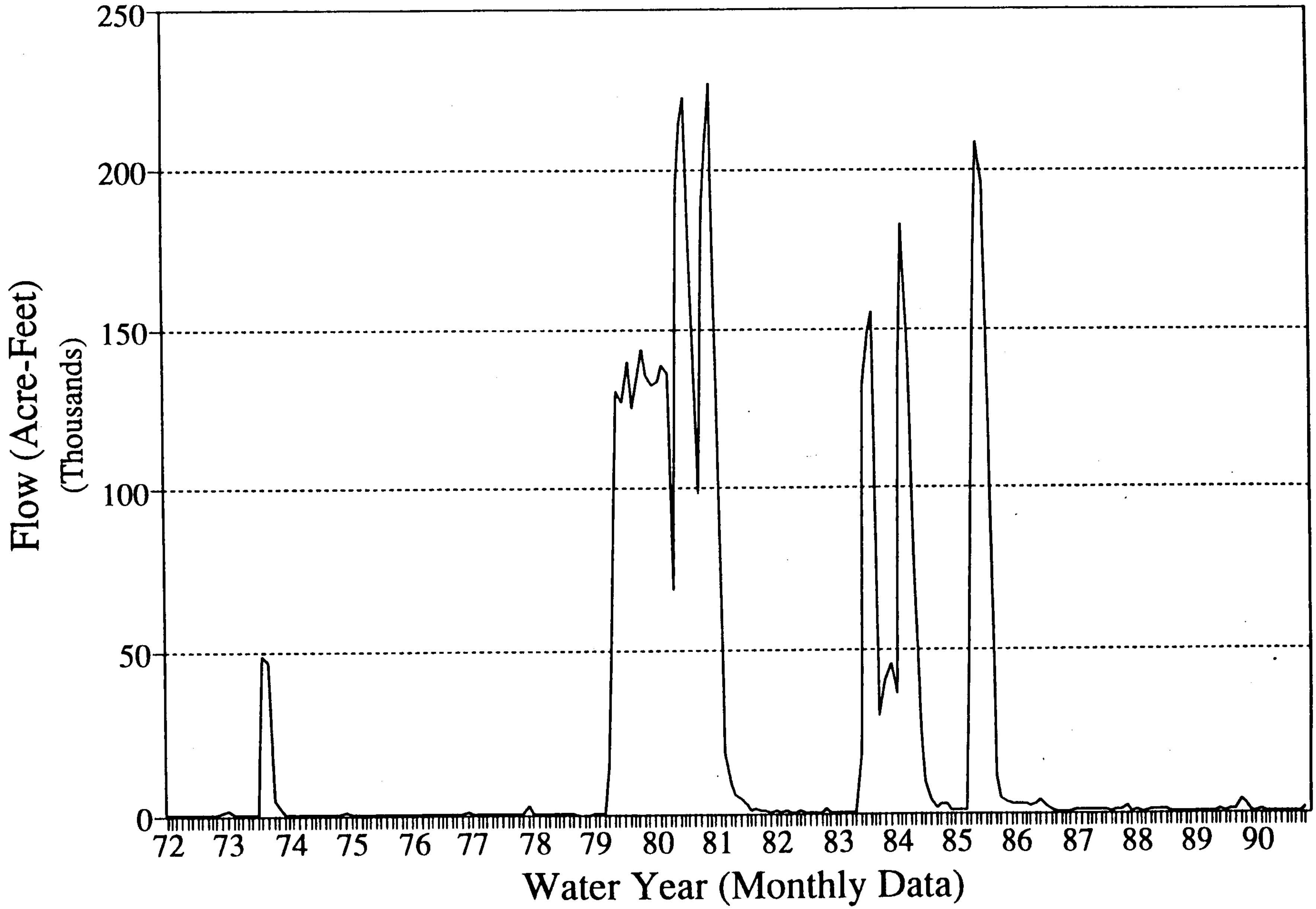
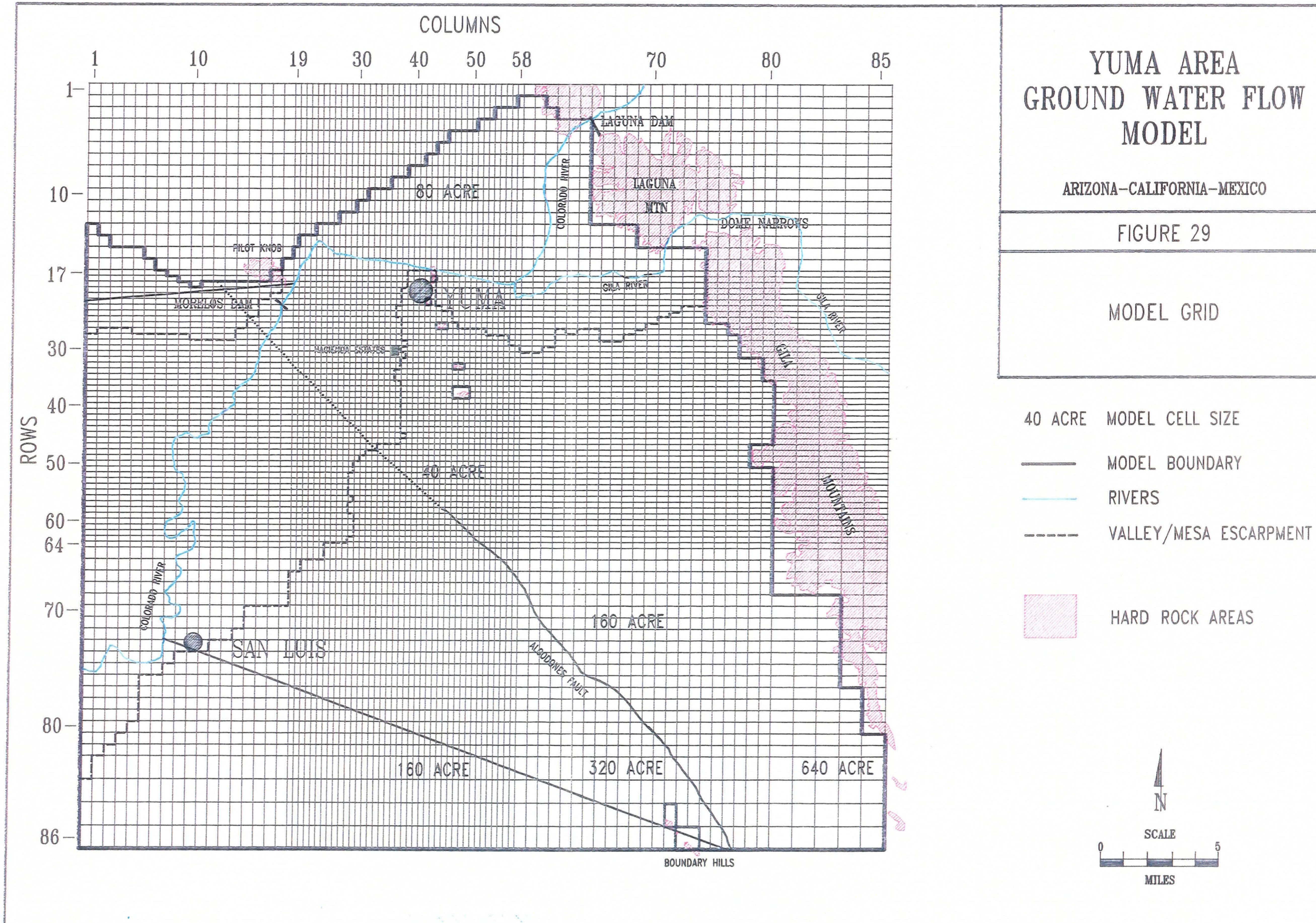
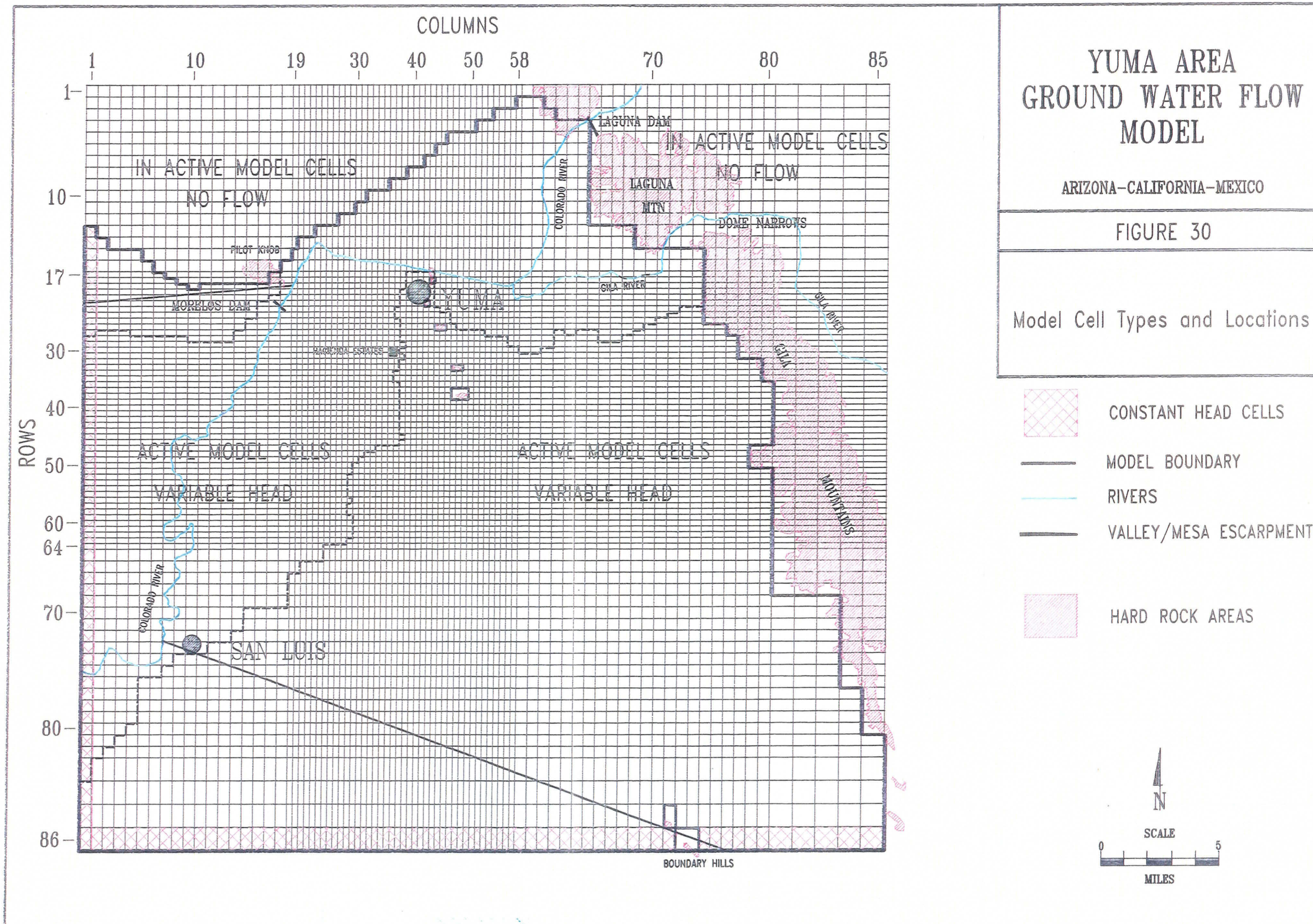


FIGURE 28. FLOW IN GILA RIVER NEAR DOME, AZ (Gage 09520500)





YUMA AREA GROUND WATER FLOW MODEL
ARIZONA-CALIFORNIA-MEXICO
FIGURE 29
MODEL GRID
COLUMNS
ROWS
80 ACRE
40 ACRE
160 ACRE
320 ACRE
640 ACRE
LAGUNA DAM
LAGUNA MTN
DOME NARROWS
COLORADO RIVER
GILA RIVER
GILA MOUNTAINS
PILOT KNOB
MORELOS DAM
YUMA
HACIENDA ESTATES
SAN LUIS
ALGODONES FAULT
BOUNDARY HILLS
40 ACRE MODEL CELL SIZE
MODEL BOUNDARY
RIVERS
VALLEY/MESA ESCARPMENT
HARD ROCK AREAS
N
SCALE
0
5
MILES

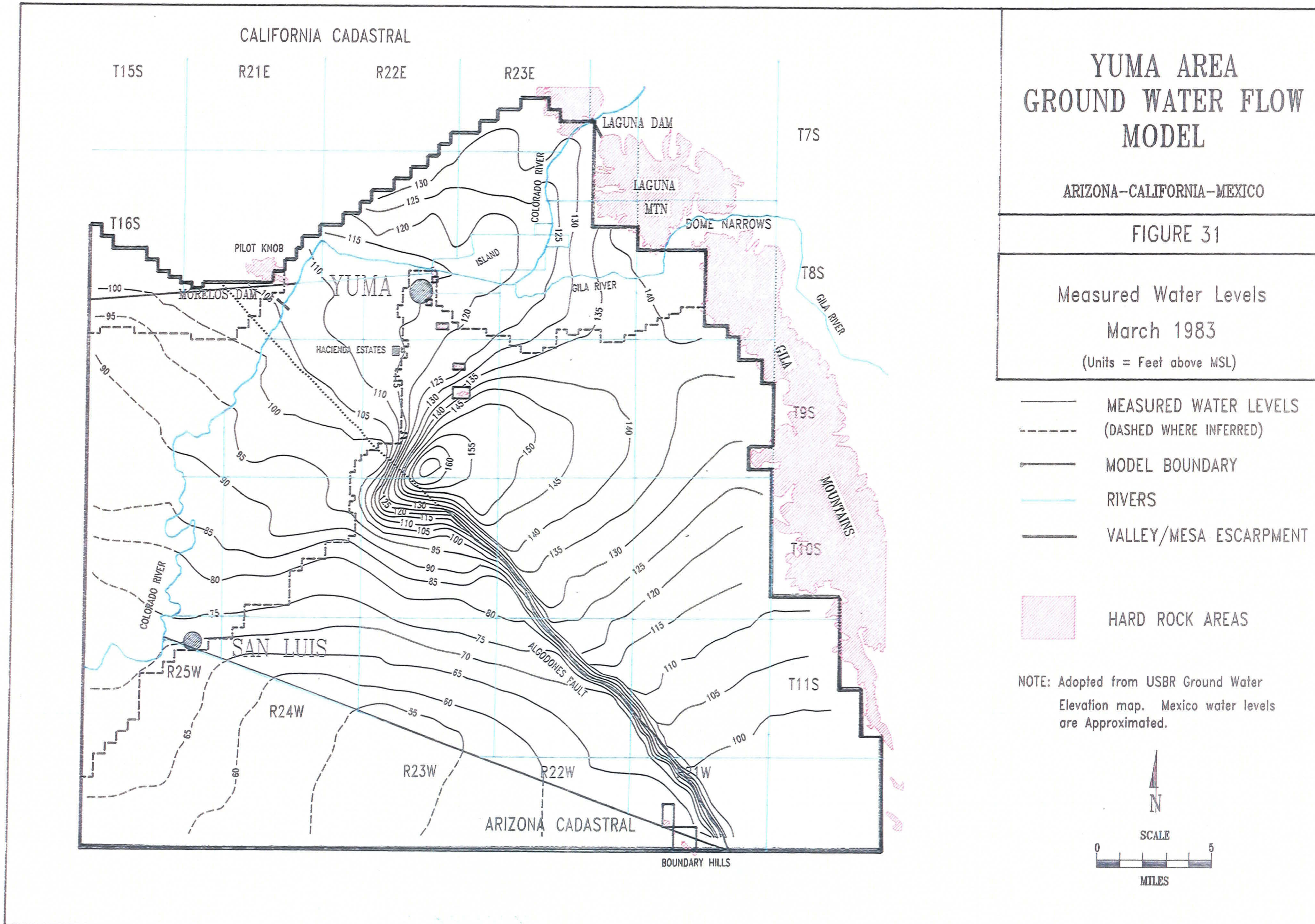


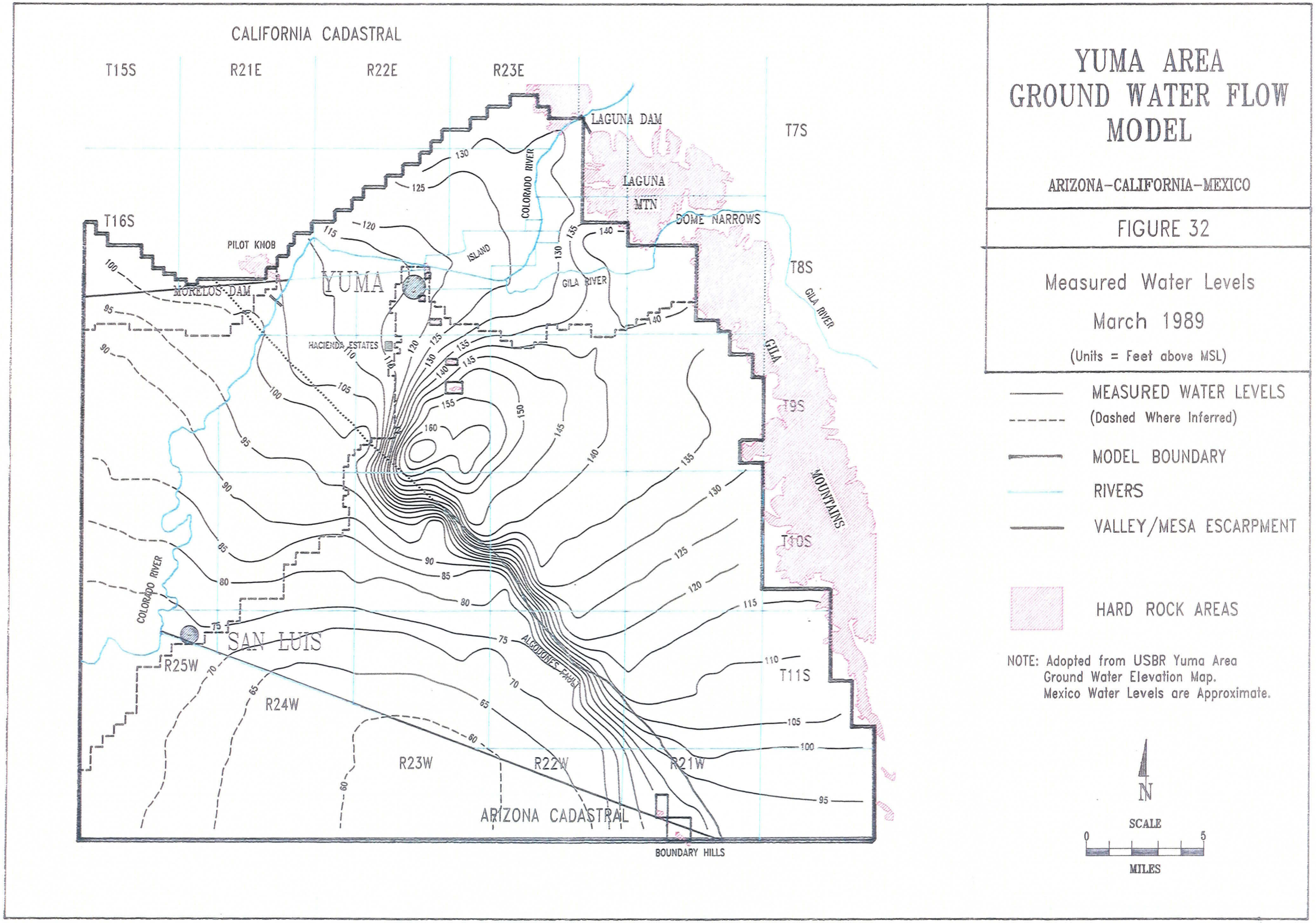
YUMA AREA GROUND WATER FLOW MODEL

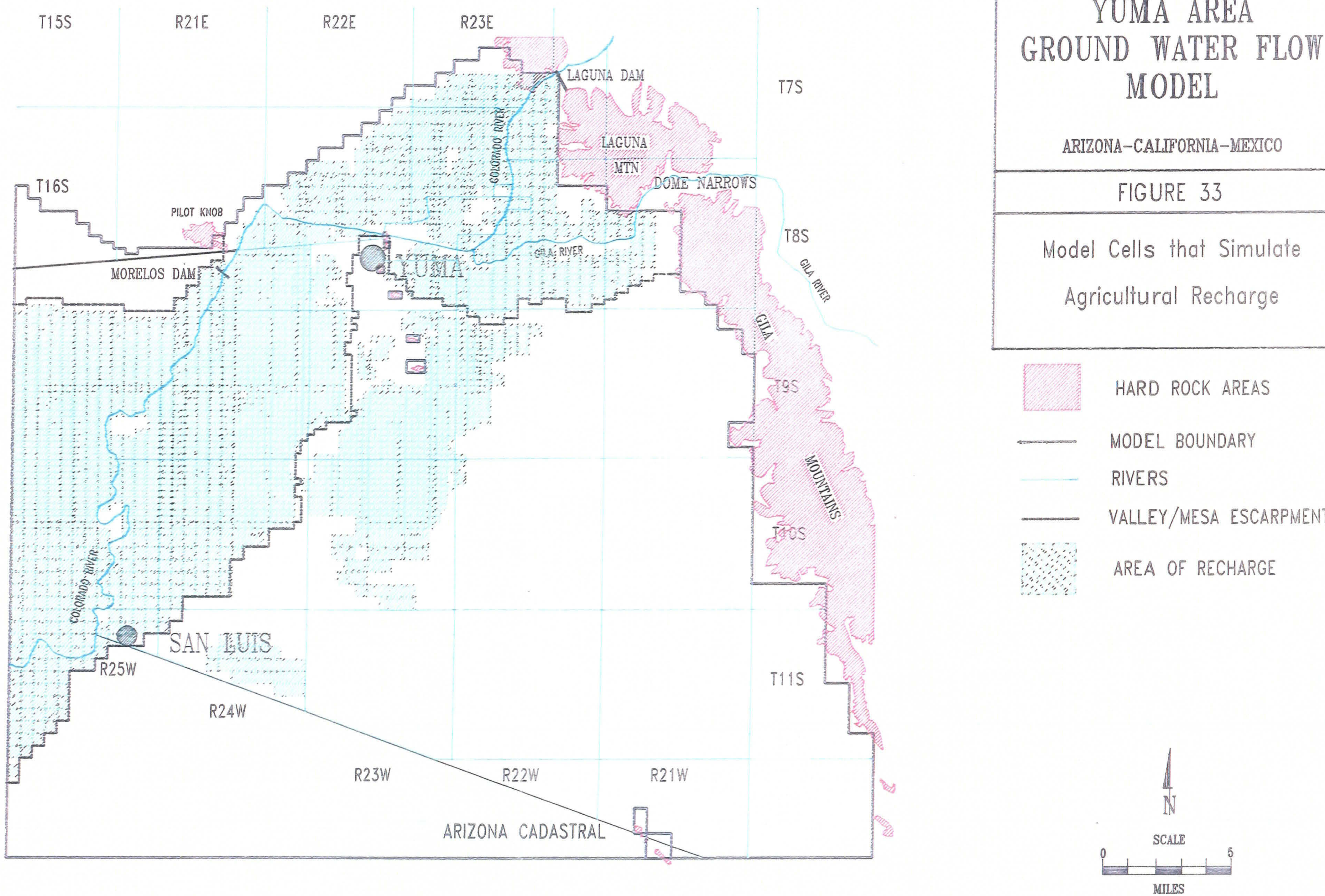
ARIZONA-CALIFORNIA-MEXICO

FIGURE 30

Model Cell Types and Locations


YUMA AREA
GROUND WATER FLOW
MODEL
ARIZONA-CALIFORNIA-MEXICO
FIGURE 31
Measured Water Levels
March 1983
(Units = Feet above MSL)
MEASURED WATER LEVELS
(DASHED WHERE INFERRED)
MODEL BOUNDARY
RIVERS
VALLEY/MESA ESCARPMENT
HARD ROCK AREAS
NOTE: Adopted from USBR Ground Water Elevation map. Mexico water levels are Approximated.
N
SCALE
0
5
MILES
CALIFORNIA CADASTRAL
T15S
R21E
R22E
R23E
T16S
T7S
T8S
T9S
T10S
T11S
LAGUNA DAM
LAGUNA
MTN
DOME NARROWS
PILOT KNOB
MORELOS DAM
YUMA
ISLAND
COLORADO RIVER
GILA RIVER
GILA
MOUNTAINS
HACIENDA ESTATES
SAN LUIS
ALGODONES FAULT
R25W
R24W
R23W
R22W
R21W
ARIZONA CADASTRAL
BOUNDARY HILLS


YUMA AREA
GROUND WATER FLOW
MODEL
ARIZONA-CALIFORNIA-MEXICO
FIGURE 32
Measured Water Levels
March 1989
(Units = Feet above MSL)
MEASURED WATER LEVELS
(Dashed Where Inferred)
MODEL BOUNDARY
RIVERS
VALLEY/MESA ESCARPMENT
HARD ROCK AREAS
NOTE: Adopted from USBR Yuma Area Ground Water Elevation Map. Mexico Water Levels are Approximate.
N
SCALE
0
5
MILES
CALIFORNIA CADASTRAL
T15S
R21E
R22E
R23E
T7S
T16S
T8S
T9S
T10S
T11S
LAGUNA DAM
LAGUNA MTN
DOME NARROWS
COLORADO RIVER
GILA RIVER
GILA MOUNTAINS
PILOT KNOB
MORELOS DAM
YUMA
ISLAND
HACIENDA ESTATES
SAN LUIS
ALGODONES FAULT
R25W
R24W
R23W
R22W
R21W
ARIZONA CADASTRAL
BOUNDARY HILLS

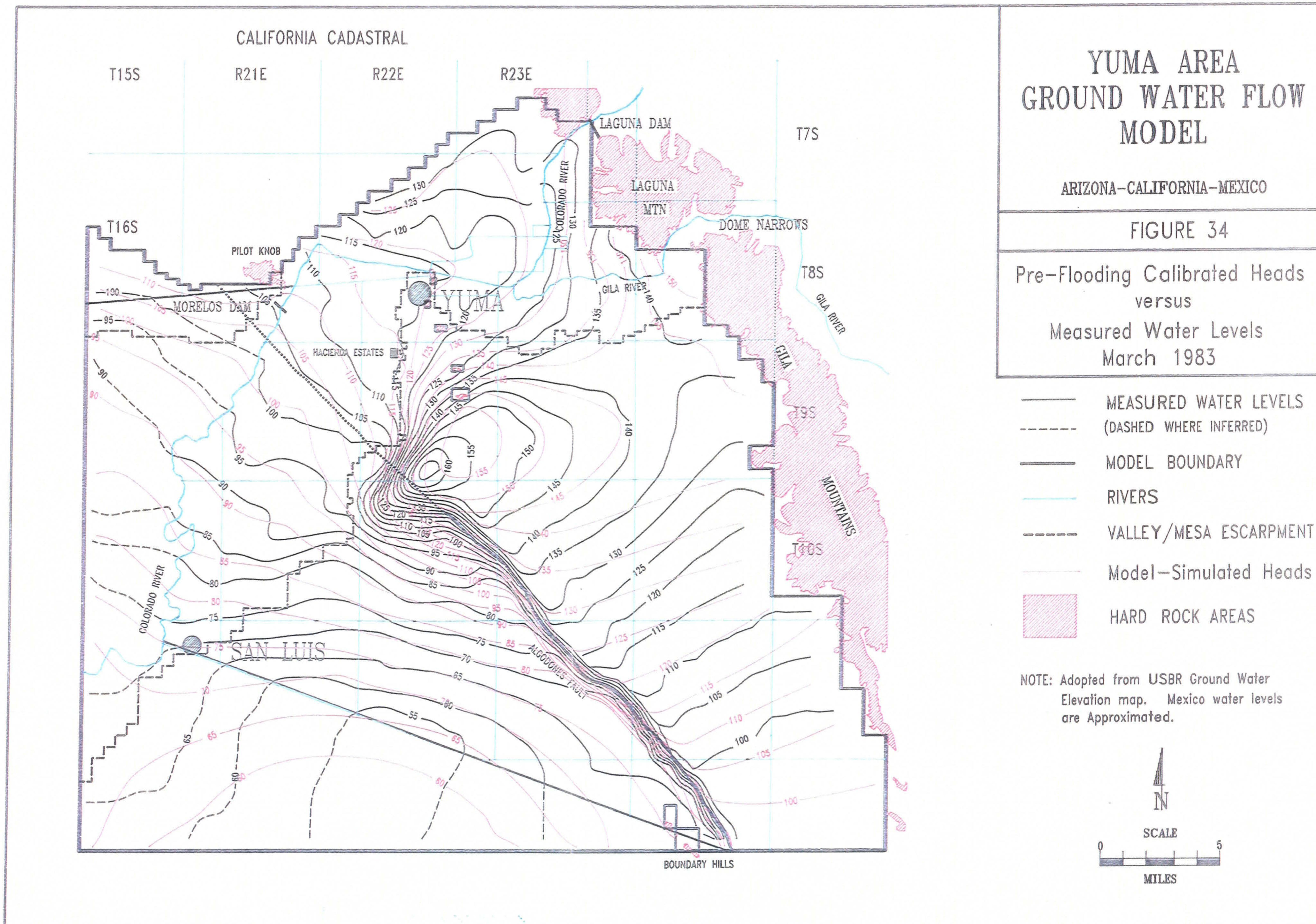


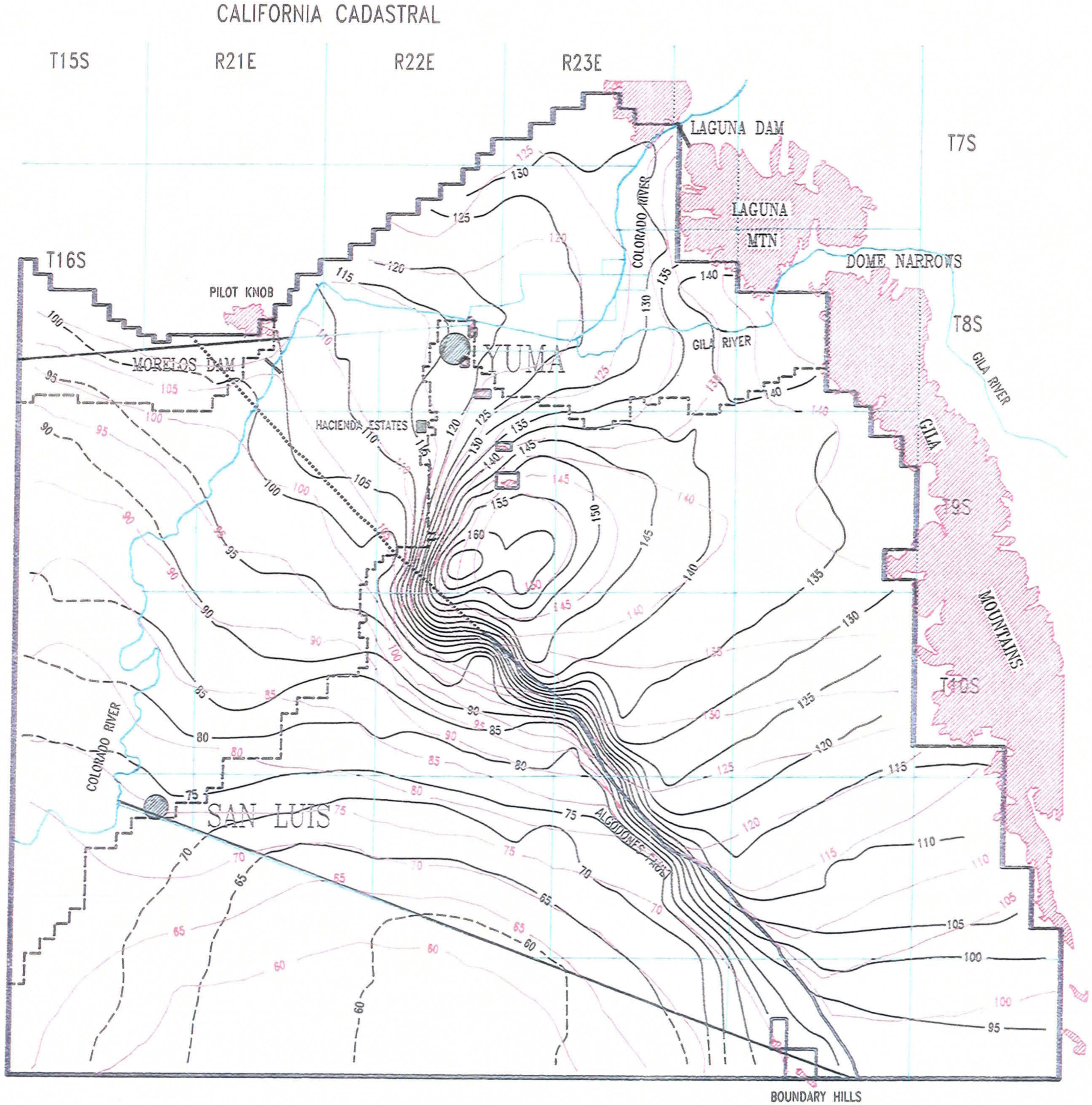
YUMA AREA GROUND WATER FLOW MODEL

ARIZONA-CALIFORNIA-MEXICO

FIGURE 33

Model Cells that Simulate Agricultural Recharge


CALIFORNIA CADASTRAL
T15S
R21E
R22E
R23E
T16S
T7S
T8S
T9S
T10S
LAGUNA DAM
LAGUNA MTN
DOME NARROWS
PILOT KNOB
MORELOS DAM
YUMA
HACIENDA ESTATES
COLORADO RIVER
GILA RIVER
GILA MOUNTAINS
ALGODONES FAULT
SAN LUIS
BOUNDARY HILLS
YUMA AREA GROUND WATER FLOW MODEL
ARIZONA-CALIFORNIA-MEXICO
FIGURE 34
Pre-Flooding Calibrated Heads versus Measured Water Levels March 1983
MEASURED WATER LEVELS (DASHED WHERE INFERRED)
MODEL BOUNDARY
RIVERS
VALLEY/MESA ESCARPMENT
Model-Simulated Heads
HARD ROCK AREAS
NOTE: Adopted from USBR Ground Water Elevation map. Mexico water levels are Approximated.
N
SCALE
0
5
MILES



YUMA AREA GROUND WATER FLOW MODEL

ARIZONA-CALIFORNIA-MEXICO

FIGURE 35

Post-Flooding Calibrated Heads versus Measured Water Levels March 1989

MEASURED WATER LEVELS (Dashed Where Inferred)

MODEL BOUNDARY

RIVERS

VALLEY/MESA ESCARPMENT

Model-Simulated Heads

HARD ROCK AREAS

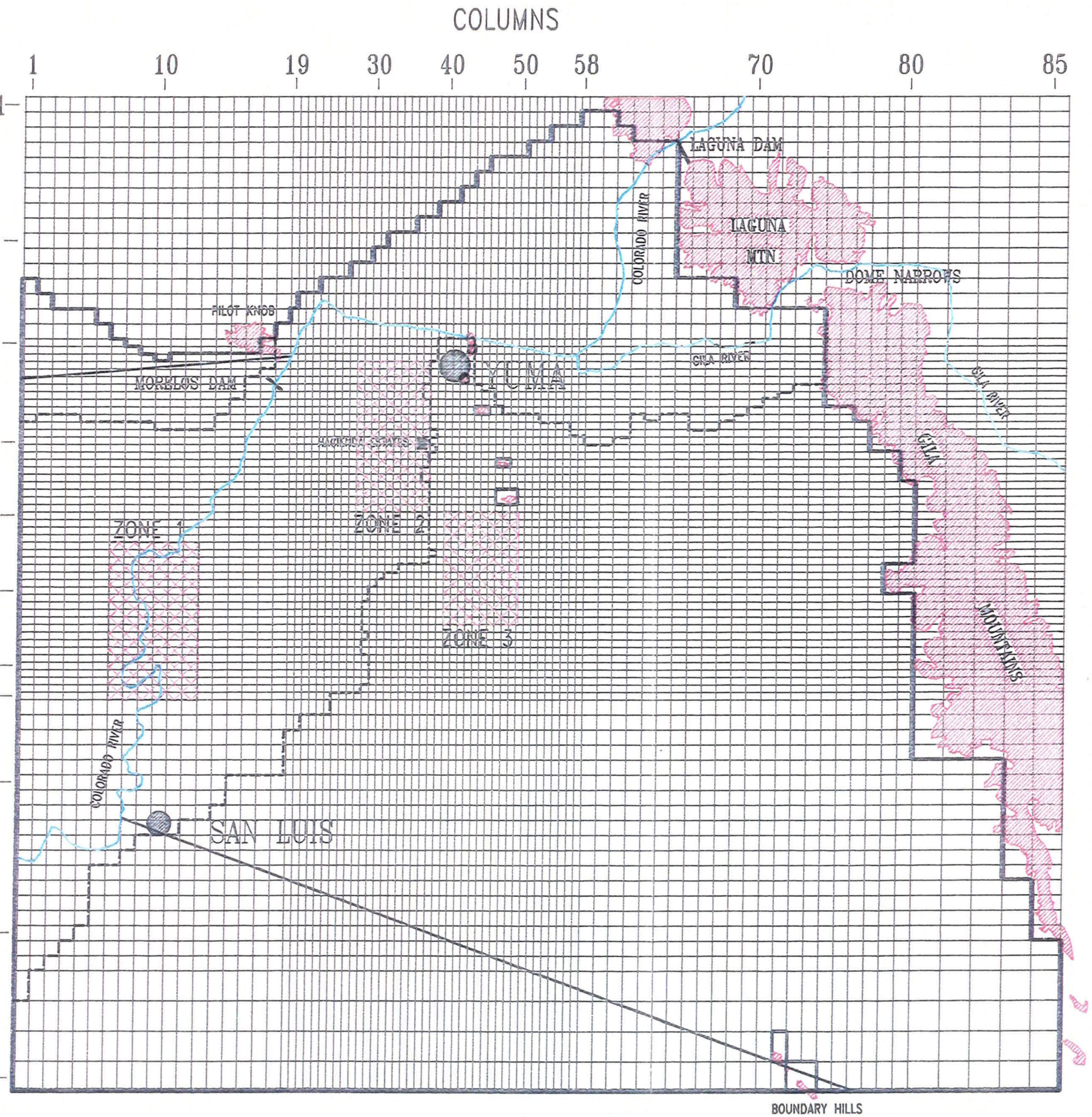
NOTE: Adopted from USBR Yuma Area Ground Water Elevation Map. Mexico Water Levels are Approximate.

N

SCALE

0 5

MILES



YUMA AREA GROUND WATER FLOW MODEL

ARIZONA-CALIFORNIA-MEXICO

FIGURE 36

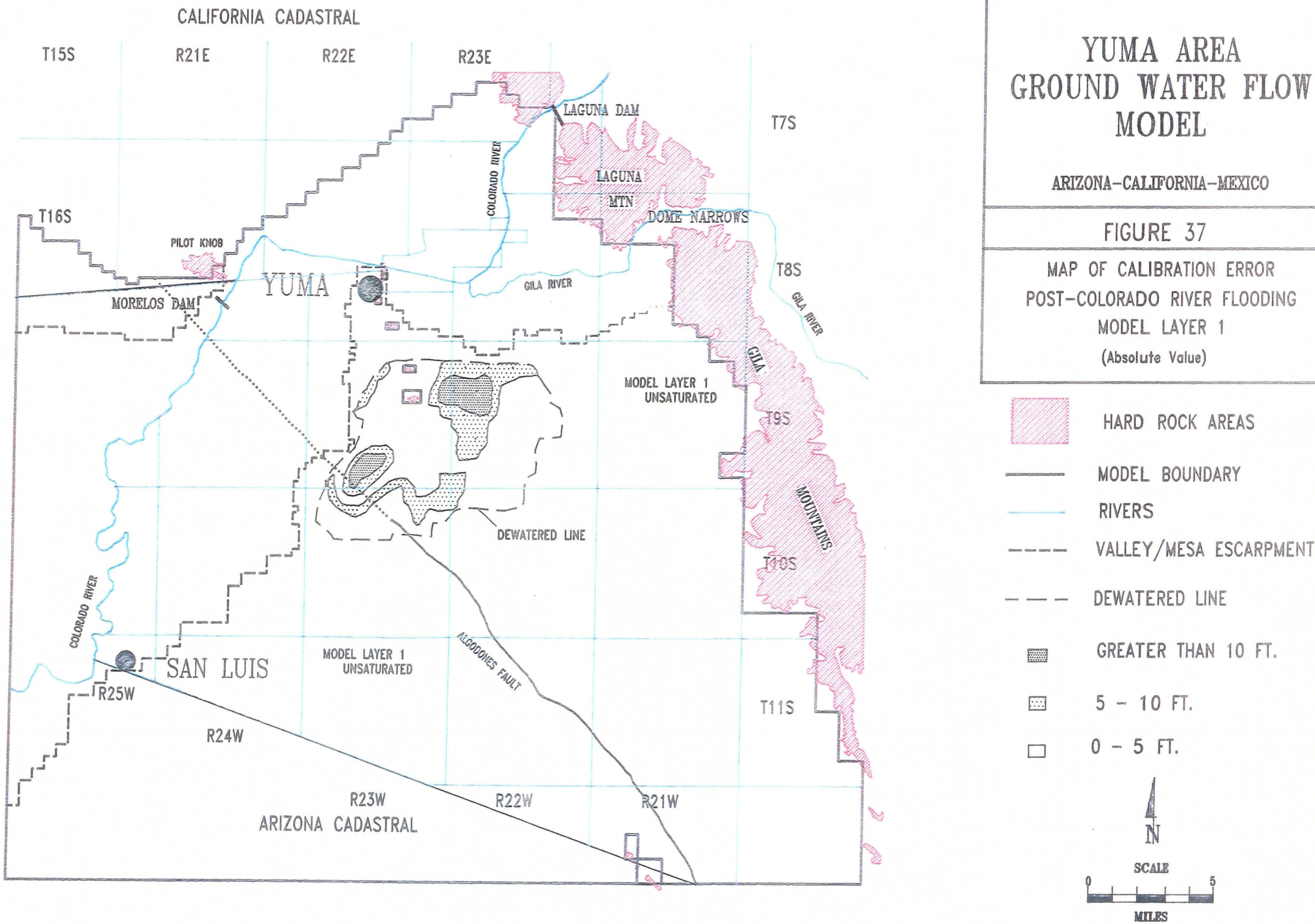
Zones for Calibration and Sensitivity Analysis

YUMA AREA GROUND WATER FLOW MODEL

ARIZONA-CALIFORNIA-MEXICO

FIGURE 37

MAP OF CALIBRATION ERROR
POST-COLORADO RIVER FLOODING
MODEL LAYER 1
(Absolute Value)

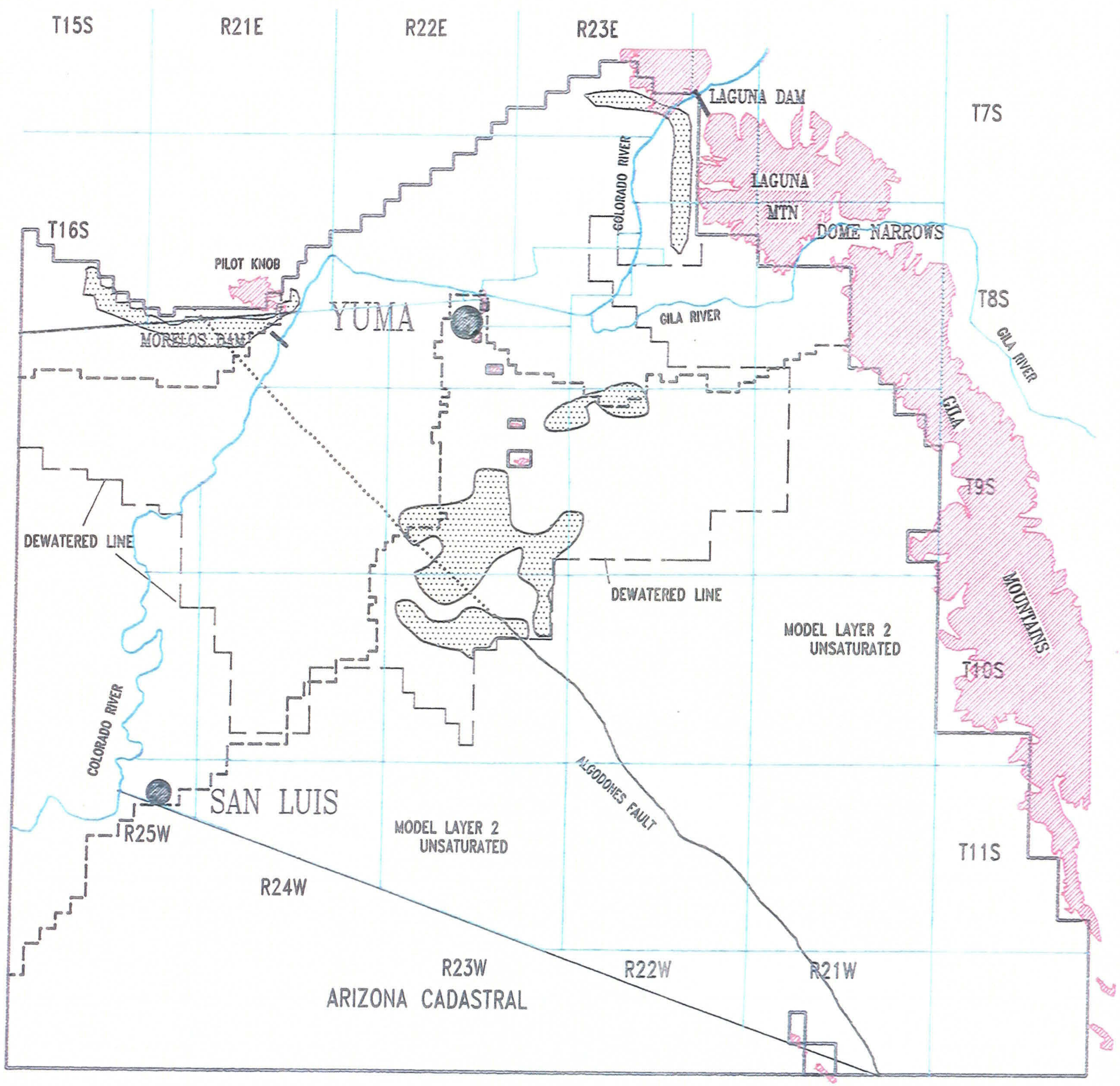


YUMA AREA GROUND WATER FLOW MODEL

ARIZONA–CALIFORNIA–MEXICO

FIGURE 38

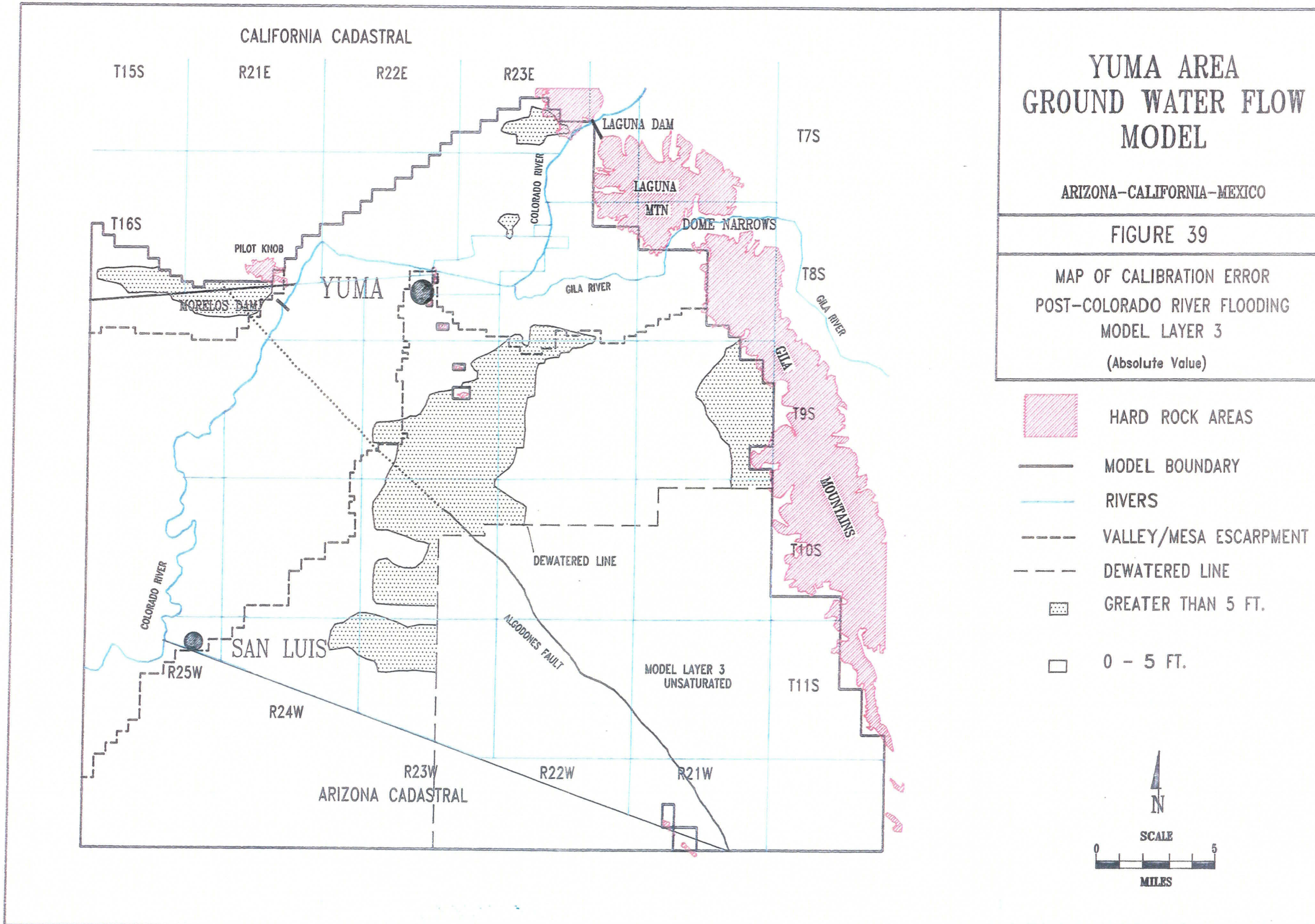
MAP OF CALIBRATION ERROR
POST-COLORADO RIVER FLOODING
MODEL LAYER 2
(Absolute Value)



HARD ROCK AREAS
MODEL BOUNDARY
RIVERS
VALLEY/MESA ESCARPMENT
DEWATERED LINE
GREATER THAN 4 FT.
0 – 4 FT.

N

SCALE 0 5 MILES



YUMA AREA
GROUND WATER FLOW
MODEL
ARIZONA-CALIFORNIA-MEXICO
FIGURE 39
MAP OF CALIBRATION ERROR
POST-COLORADO RIVER FLOODING
MODEL LAYER 3
(Absolute Value)
HARD ROCK AREAS
MODEL BOUNDARY
RIVERS
VALLEY/MESA ESCARPMENT
DEWATERED LINE
GREATER THAN 5 FT.
0 - 5 FT.
CALIFORNIA CADASTRAL
T15S
R21E
R22E
R23E
LAGUNA DAM
T7S
LAGUNA
MTN
DOME NARROWS
COLORADO RIVER
T16S
PILOT KNOB
YUMA
MORELOS DAM
GILA RIVER
T8S
GILA RIVER
GILA
MOUNTAINS
T9S
T10S
DEWATERED LINE
ALGODONES FAULT
MODEL LAYER 3
UNSATURATED
T11S
COLORADO RIVER
SAN LUIS
R25W
R24W
R23W
R22W
R21W
ARIZONA CADASTRAL
N
SCALE
0
5
MILES

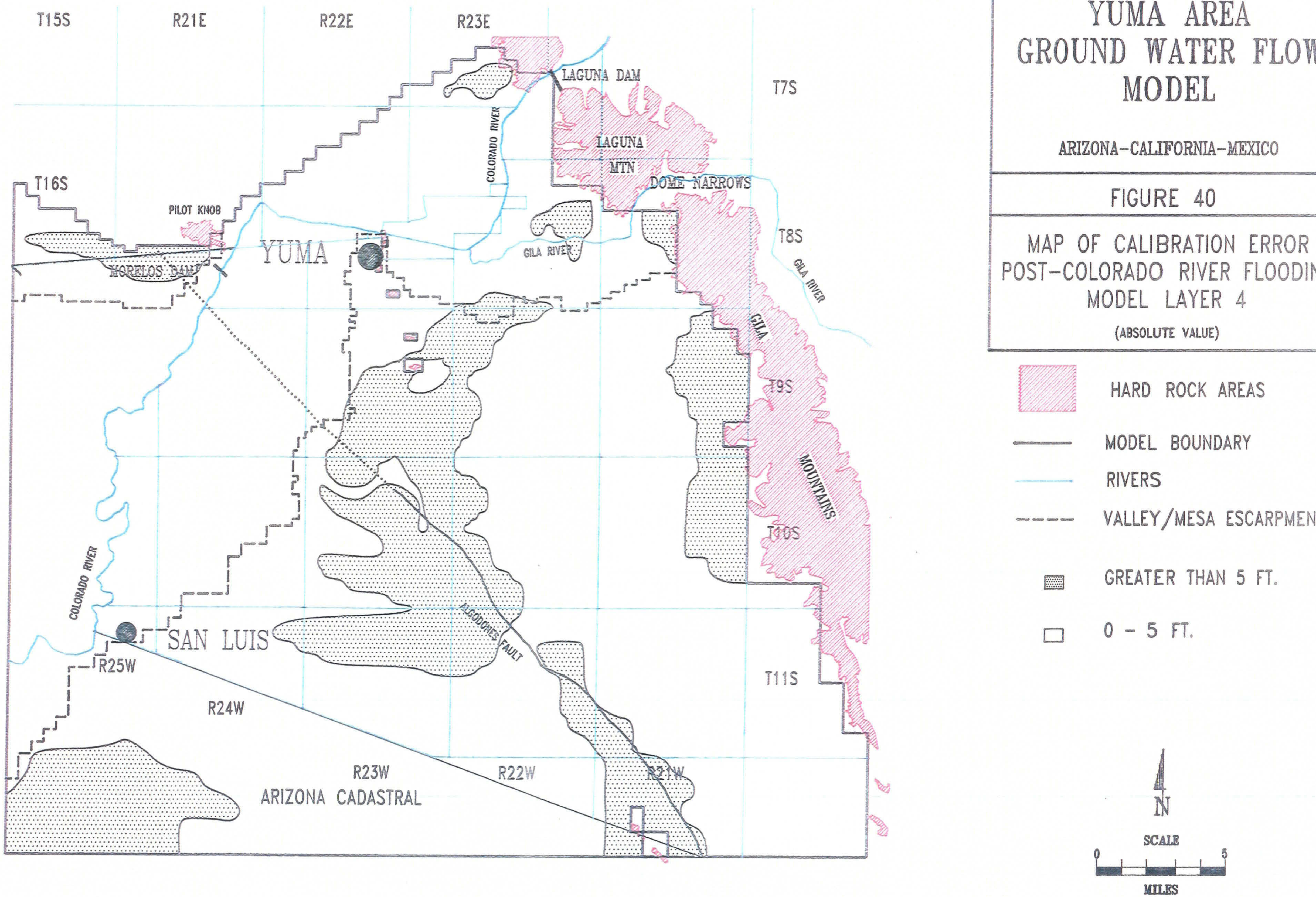
YUMA AREA GROUND WATER FLOW MODEL

ARIZONA-CALIFORNIA-MEXICO

FIGURE 40

MAP OF CALIBRATION ERROR POST-COLORADO RIVER FLOODING MODEL LAYER 4

(ABSOLUTE VALUE)



APPENDIX II USBR/ADWR AQUIFER PUMPING TESTS

The U.S. Bureau of Reclamation in cooperation with the Arizona Department of Water Resources conducted several short-term, multiple-well aquifer pumping tests at six locations within the Yuma area. These tests were conducted to better understand the hydraulic characteristics of the upper, fine-grained zone and provide valuable input data for the groundwater flow model. Five of the tests were conducted within Yuma Valley and one on Yuma Mesa (Figure 13).

Design of aquifer pumping tests is critical to obtaining valid results. Each aquifer pumping tests consisted of two observation wells and one pumping well completed at the same depth below land surface. Each well was 2.5 inches in diameter and generally completed between 30 and 45 feet below land surface within the upper, fine-grained zone (i.e., model Layer 3 in Yuma Valley and model Layer 1 on Yuma Mesa). The observation wells were located within a radius of five to 12 feet from the pumping well. The screened length for the pumping well was generally four feet and the observation well two feet.

The pumping well was pumped at a constant discharge rate between 16 and 65 gallons per minute (GPM) for approximately one hour. Cessation of pumping occurred after water levels stabilized within the observation wells. The short duration of these tests was due to the small diameter of the pumping well and minimal screen length which limited the ability to stress the aquifer at discharge rates greater than 65 GPM.

Drawdown and recovery data from the observation wells were analyzed using a variety of analytical techniques including manual graphing and AQTESOLV software developed by Geraghty and Miller (Duffield and Rumbaugh, 1991). The analytical techniques included Theis (1935), Cooper-Jacob (1946) straight-line method, Neuman (1975) unconfined delayed yield, and Neuman (1975) with effects of partial penetration.

The results of the aquifer pumping tests are summarized in the table provided below. Aquifer transmissivity was estimated from each test and varies slightly depending upon the analytical solution. Transmissisvity estimates average 7,000 FT^2/Day in northern Yuma Valley and increase towards the southwest averaging 9,200 FT^2/Day. Transmissivity was calculated at an average of 2,700 FT^2/Day adjacent to the East Main canal. However, the drawdown data indicate the influence of a recharging boundary which may have effected the results.

Horizontal hydraulic conductivity was estimated by dividing the transmissivity by the aquifer thickness which was assumed to be the distance from the bottom of the well to the static water level. Estimates of horizontal to vertical hydraulic conductivity were attempted using the Neuman (1975) analytical method contained in AQTESOLV. However, these estimates were unrealistically too low and were determined invalid. Valid estimates of aquifer storage coefficient could not be obtained from these pumping tests. The short duration of these tests underestimated the aquifer storage coefficient. Kruseman and deRidder (1991) state to obtain a representative storage coefficient from unconfined aquifers they should be pumped for several days to reach near steady state conditions.

Several limitations must be considered when analyzing the results from these pumping tests. First, the transmissivity estimates for the upper, fine-grained zone are probably under-estimated because of the relatively small area of hydraulic influence due to the short duration of the tests. Second, the effects of partial penetration by both the pumping and observation wells must be considered. Pumping an unconfined aquifer with a partially penetrating well induces a significant vertical component of flow which invalidates the Theis assumption of horizontal flow (Kruseman and deRidder, 1991). This vertical component of flow leads to excess loss of head in the aquifer (i.e., larger measurement of drawdown) which can influence the estimate of aquifer transmissivity. Third, recharge boundary conditions was evident in one of two tests conducted adjacent to the unlined East Main canal which may have influenced the results.

Summary of USBR/ADWR Aquifer Pumping Tests

SITE No. 1: Yuma Valley, U.S.B.R. YPO Desalting Plant
Date: July, 1991

Discharge Rate: 27 gpm
Observation well BH1-AA: 5 feet radius from pumping well
Observation well OB2-AA: 11 feet radius from pumping well
Aquifer Thickness: 30 Ft

SITE No. 1 (CONT): Yuma Valley, U.S.B.R. YPO Desalting Plant
Date: July, 1991

Observation Well	Transmissivity	Hydraulic Conductivity	Analytical Technique
BH1-AA	5000 Ft^2/Day	170 Ft/Day	Drawdown (Cooper-Jacob, 1946)
BH1-AA	7600 Ft^2/Day	250 Ft/Day	Recovery
OB2-AA	6800 Ft^2/Day	230 Ft/Day	Drawdown (Cooper-Jacob, 1946)
OB2-AA	6800 Ft^2/Day	230 Ft/Day	Recovery

SITE No. 2: Yuma Valley, Hacienda Estates
Date: July, 1991

Discharge Rate: 65 gpm
Observation well OBS-1: 4.9 feet radius from pumping well
Observation well OBS-2: 10.9 feet radius from pumping well
Aquifer Thickness: 20 Ft

Observation Well	Transmissivity	Hydraulic Conductivity	Analytical Technique
OBS-1	6400 Ft^2/Day	320 Ft/Day	Drawdown (Cooper-Jacob, 1946)
OBS-2	6500 Ft^2/Day	330 Ft/Day	Drawdown (Cooper-Jacob, 1946)
OBS-2	10000 Ft^2/Day	500 Ft/Day	Recovery

SITE No. 3: Yuma Valley, 13.5 Street next to East Main Canal
Date: June, 1992

Discharge Rate: 38 gpm
Observation well 13.5-2: 5.4 feet radius from pumping well
Observation well 13.5-1: 11.5 feet radius from pumping well
Aquifer Thickness: 35 Ft

SITE No. 3 (CONT): Yuma Valley, 13.5 Street next to East Main Canal
Date: June, 1992

Observation Well	Transmissivity	Hydraulic Conductivity	Analytical Technique
13.5-2	3600 Ft^2/Day	100 Ft/Day	Drawdown (Cooper-Jacob, 1946)
13.5-2	2500 Ft^2/Day	70 Ft/Day	Recovery
13.5-2	2900 Ft^2/Day	80 Ft/Day	Drawdown (AQTESOLV: Cooper-Jacob, 1946)
13.5-2	2900 Ft^2/Day	80 Ft/Day	Drawdown (AQTESOLV: Theis, 1935)
13.5-2	2200 Ft^2/Day	60 Ft/Day	Drawdown (AQTESOLV: Neuman, 1975 with effects from partial penetration)
13.5-1	1600 Ft^2/Day	50 Ft/Day	Drawdown (Cooper-Jacob, 1946)
13.5-1	2300 Ft^2/Day	70 Ft/Day	Recovery
13.5-1	3500 Ft^2/Day	100 Ft/Day	Drawdown (AQTESOLV: Cooper-Jacob, 1946)

SITE No. 4: Yuma Mesa, Yuma Mesa Irrigation District Maintenance Yard
Date: June, 1992

Discharge Rate: 16 gpm
Observation well YMID-2: 5.6 feet radius from pumping well
Observation well YMID-3: 11.3 feet radius from pumping well
Aquifer Thickness: 30 Ft

Observation Well	Transmissivity	Hydraulic Conductivity	Analytical Technique
YMID-2	6300 Ft^2/Day	210 Ft/Day	Drawdown (Cooper-Jacob, 1946)
YMID-2	6300 Ft^2/Day	210 Ft/Day	Recovery
YMID-3	5600 Ft^2/Day	190 Ft/Day	Drawdown (Cooper-Jacob, 1946)
YMID-3	4300 Ft^2/Day	140 Ft/Day	Recovery

SITE No. 5: Yuma Valley, 18th Street and H 1/2 Street, next to Cummings canal
Date: June, 1992

Discharge Rate: 30 gpm
Observation well 18-2: 5.2 feet radius from pumping well
Observation well 18-3: 9.9 feet radius from pumping well
Aquifer Thickness: 35 Ft

SITE No. 5 (CONT): Yuma Valley, 18th Street and H 1/2 Street, next to Cummings canal
Date: June, 1992

Observation Well	Transmissivity	Hydraulic Conductivity	Analytical Technique
18-2	9600 Ft^2/Day	270 Ft/Day	Drawdown (Cooper-Jacob, 1946)
18-2	10600 Ft^2/Day	300 Ft/Day	Recovery
18-2	8800 Ft^2/Day	250 Ft/Day	Drawdown (AQTESOLV: Neuman, 1975)
18-3	9600 Ft^2/Day	270 Ft/Day	Drawdown (Cooper-Jacob, 1946)
18-3	10600 Ft^2/Day	300 Ft/Day	Recovery
18-3	10700 Ft^2/Day	300 Ft/Day	Drawdown (AQTESOLV: Cooper-Jacob, 1946)
18-3	7400 Ft^2/Day	210 Ft/Day	Drawdown (AQTESOLV: Theis, 1935)
18-3	6400 Ft^2/Day	180 Ft/Day	Drawdown (AQTESOLV: Neuman, 1975 with effects from partial penetration)

SITE No. 6: Yuma Valley, 13th Street near YCWUA 13 well
Date: June, 1992

Discharge Rate: 18 gpm
Observation well OBS-1: 5.6 feet radius from pumping well
Observation well OBS-2: 10.8 feet radius from pumping well
Aquifer Thickness: 40 Ft

Observation Well	Transmissivity	Hydraulic Conductivity	Analytical Technique
OBS-1	4500 Ft^2/Day	110 Ft/Day	Drawdown (Cooper-Jacob, 1946)
OBS-1	5300 Ft^2/Day	130 Ft/Day	Recovery
OBS-2	6300 Ft^2/Day	160 Ft/Day	Drawdown (Cooper-Jacob, 1946)

REFERENCES

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

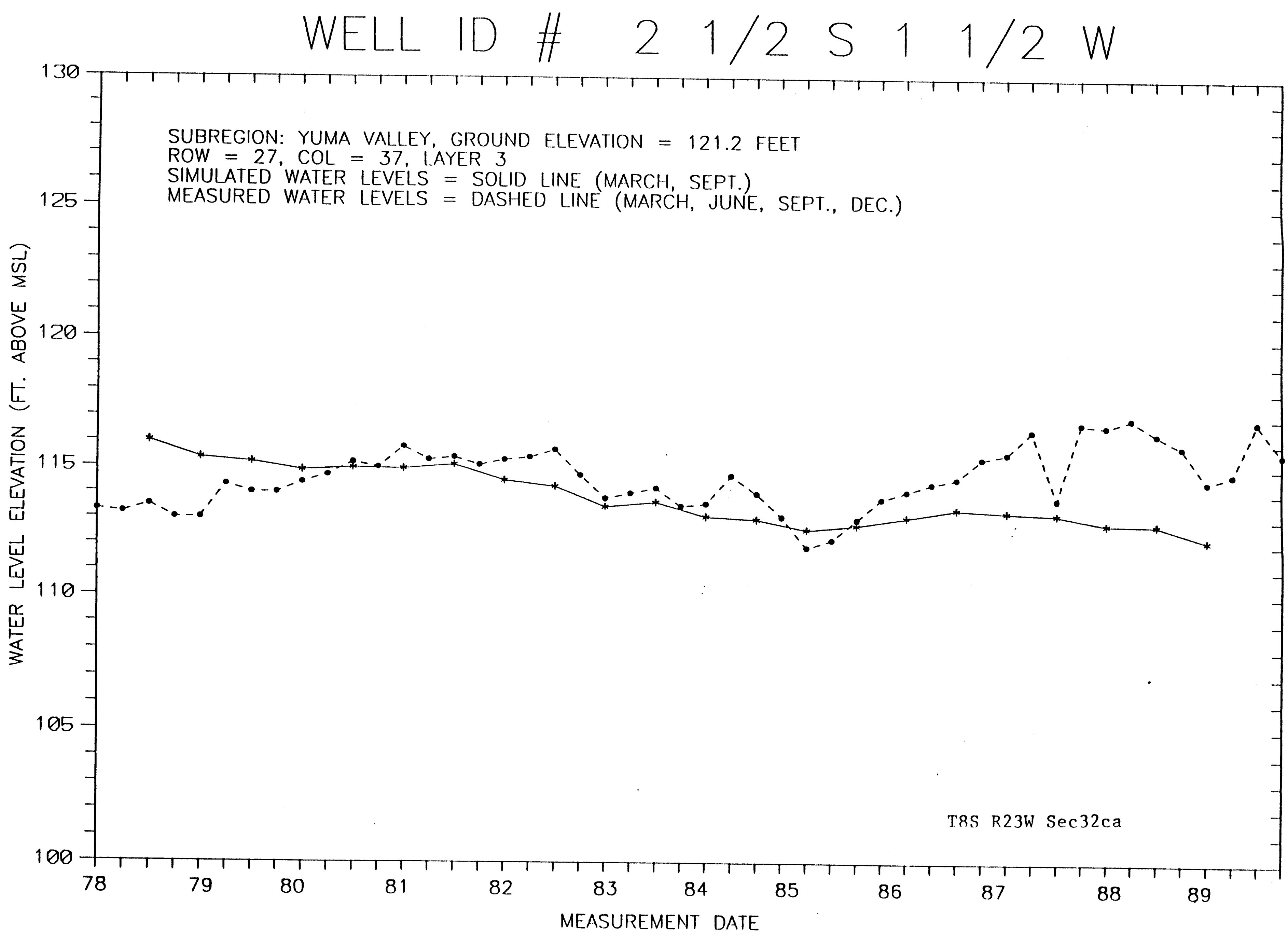
Duffield, G.M. and J.O. Rumbaugh, 1991, AQTESOLV - Aquifer Test Design and Analysis Computer Software: Geraghty and Miller, Inc., Reston, Virginia (703) 758-1200.

Kruseman, G.P., and N.A. deRidder, 1991, Analysis and Evaluation of Pumping Test Data, Second Edition: International Institute for Land Reclamation and Improvement, Netherlands, 377p.

Neuman, S.P., 1975, Analysis of pumping test data from anisotropic unconfined aquifers considering delayed yield, Water Resources Research, vol. 11, no. 2, pp. 329-342.

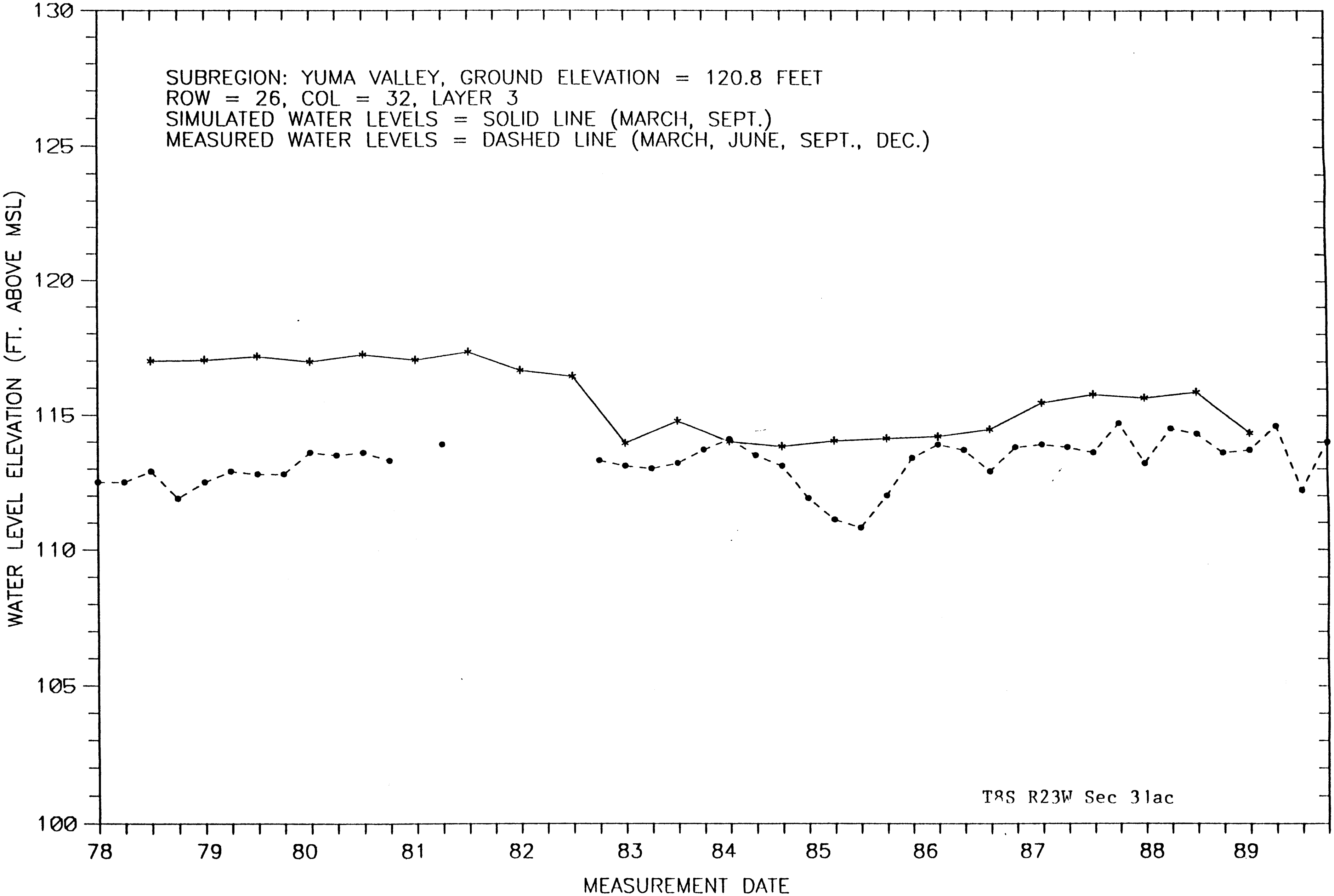
Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage: Trans. American Geophysics Union, vol. 16, pp. 519-524.

APPENDIX III HYDROGRAPHS



WELL ID # 2 1/2 S 1 1/2 W
SUBREGION: YUMA VALLEY, GROUND ELEVATION = 121.2 FEET
ROW = 27, COL = 37, LAYER 3
SIMULATED WATER LEVELS = SOLID LINE (MARCH, SEPT.)
MEASURED WATER LEVELS = DASHED LINE (MARCH, JUNE, SEPT., DEC.)
WATER LEVEL ELEVATION (FT. ABOVE MSL)
130
125
120
115
110
105
100
78
79
80
81
82
83
84
85
86
87
88
89
MEASUREMENT DATE
T8S R23W Sec32ca

WELL ID # 2 1/2 S 2 1/2 W



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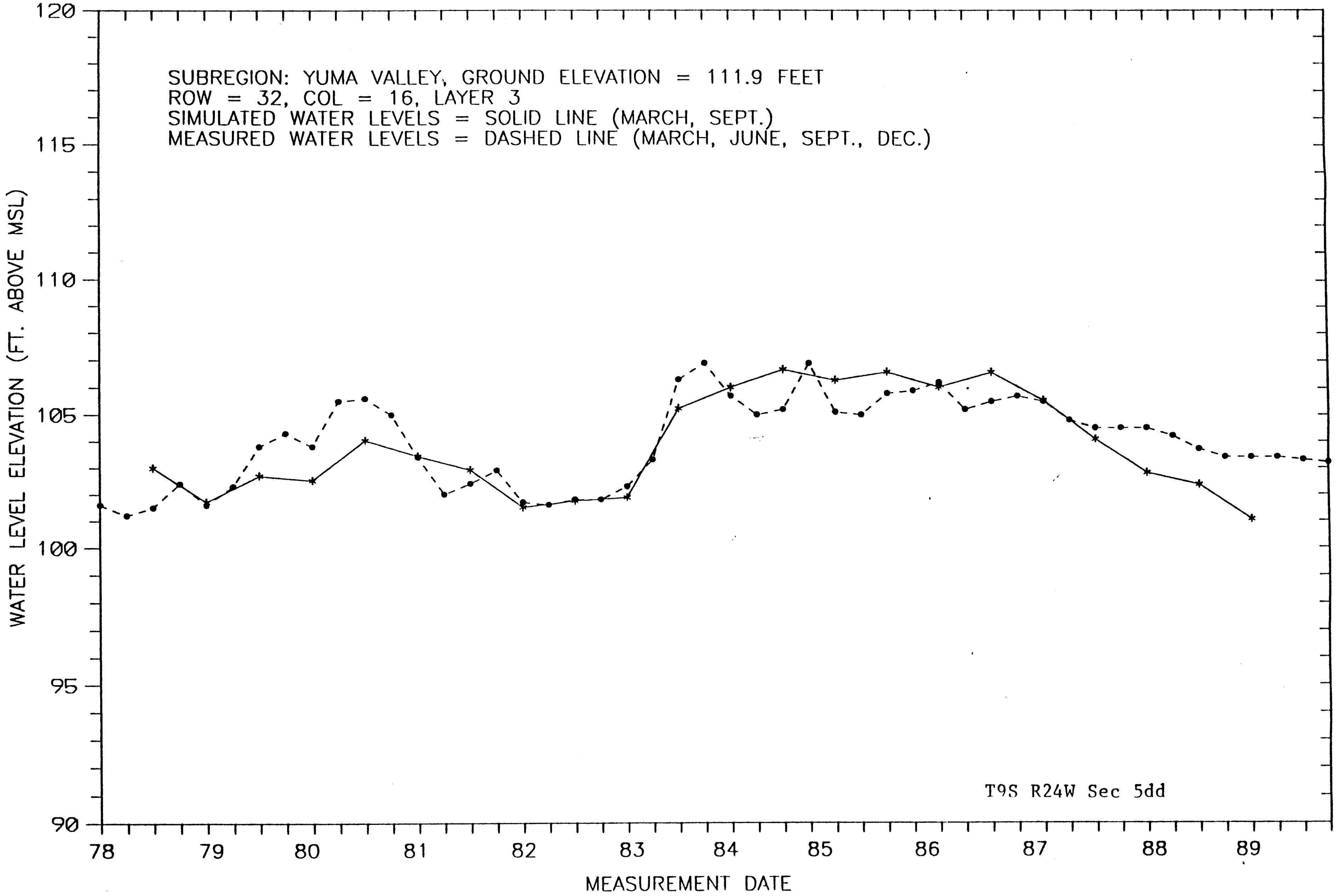
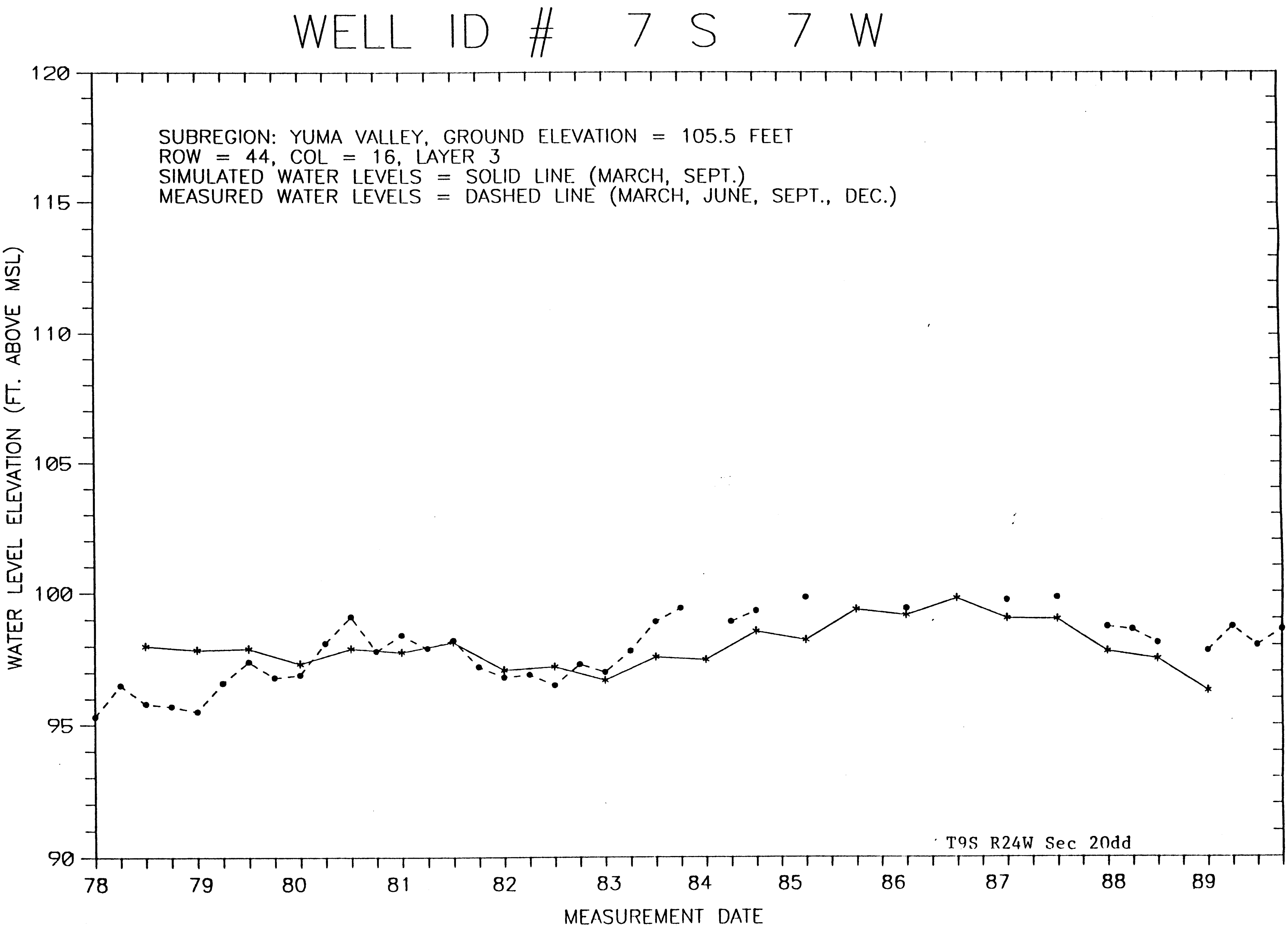

SUBREGION: YUMA VALLEY, GROUND ELEVATION = 111.9 FEET
ROW = 32, COL = 16, LAYER 3
SIMULATED WATER LEVELS = SOLID LINE (MARCH, SEPT.)
MEASURED WATER LEVELS = DASHED LINE (MARCH, JUNE, SEPT., DEC.)
WATER LEVEL ELEVATION (FT. ABOVE MSL)
120
115
110
105
100
95
90
78
79
80
81
82
83
84
85
86
87
88
89
MEASUREMENT DATE
T9S R24W Sec 5dd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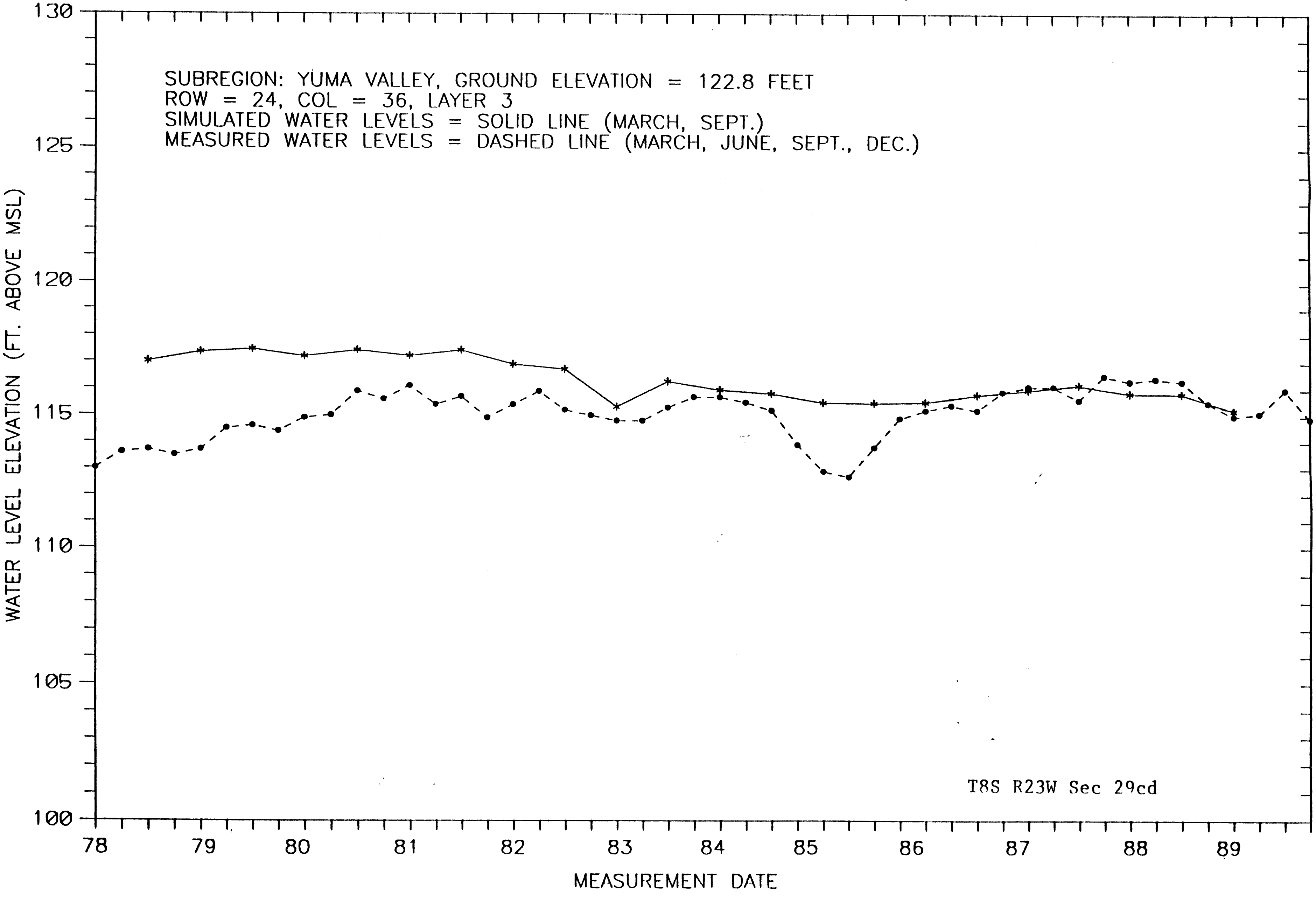
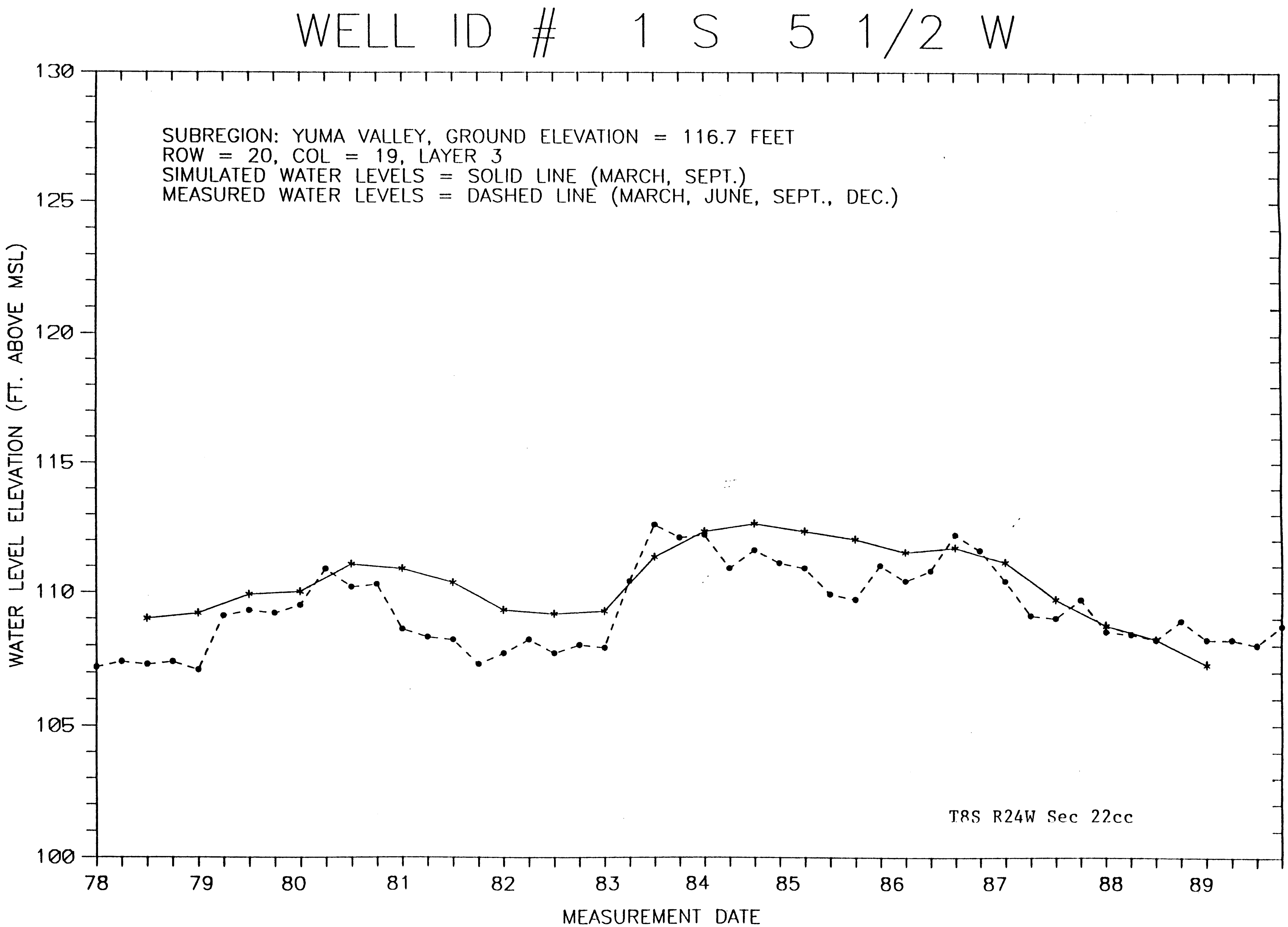
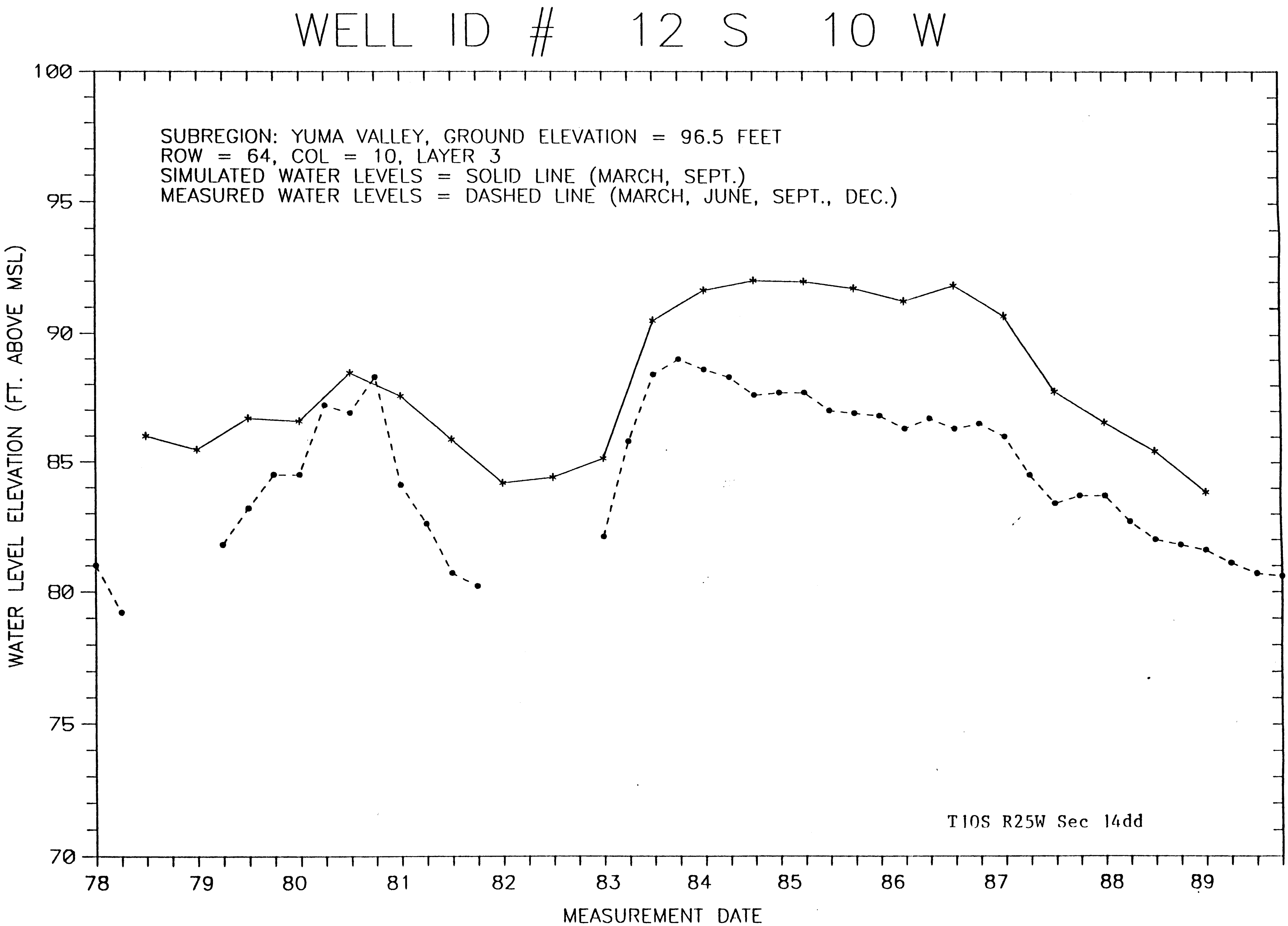
SUBREGION: YUMA VALLEY, GROUND ELEVATION = 105.5 FEET
ROW = 44, COL = 16, LAYER 3
SIMULATED WATER LEVELS = SOLID LINE (MARCH, SEPT.)
MEASURED WATER LEVELS = DASHED LINE (MARCH, JUNE, SEPT., DEC.)
WATER LEVEL ELEVATION (FT. ABOVE MSL)
120
115
110
105
100
95
90
78
79
80
81
82
83
84
85
86
87
88
89
MEASUREMENT DATE
T9S R24W Sec 20dd

WELL ID # 2 S 1 1/2 W




WELL ID # 1 S 5 1/2 W
SUBREGION: YUMA VALLEY, GROUND ELEVATION = 116.7 FEET
ROW = 20, COL = 19, LAYER 3
SIMULATED WATER LEVELS = SOLID LINE (MARCH, SEPT.)
MEASURED WATER LEVELS = DASHED LINE (MARCH, JUNE, SEPT., DEC.)
WATER LEVEL ELEVATION (FT. ABOVE MSL)
130
125
120
115
110
105
100
78
79
80
81
82
83
84
85
86
87
88
89
MEASUREMENT DATE
T8S R24W Sec 22cc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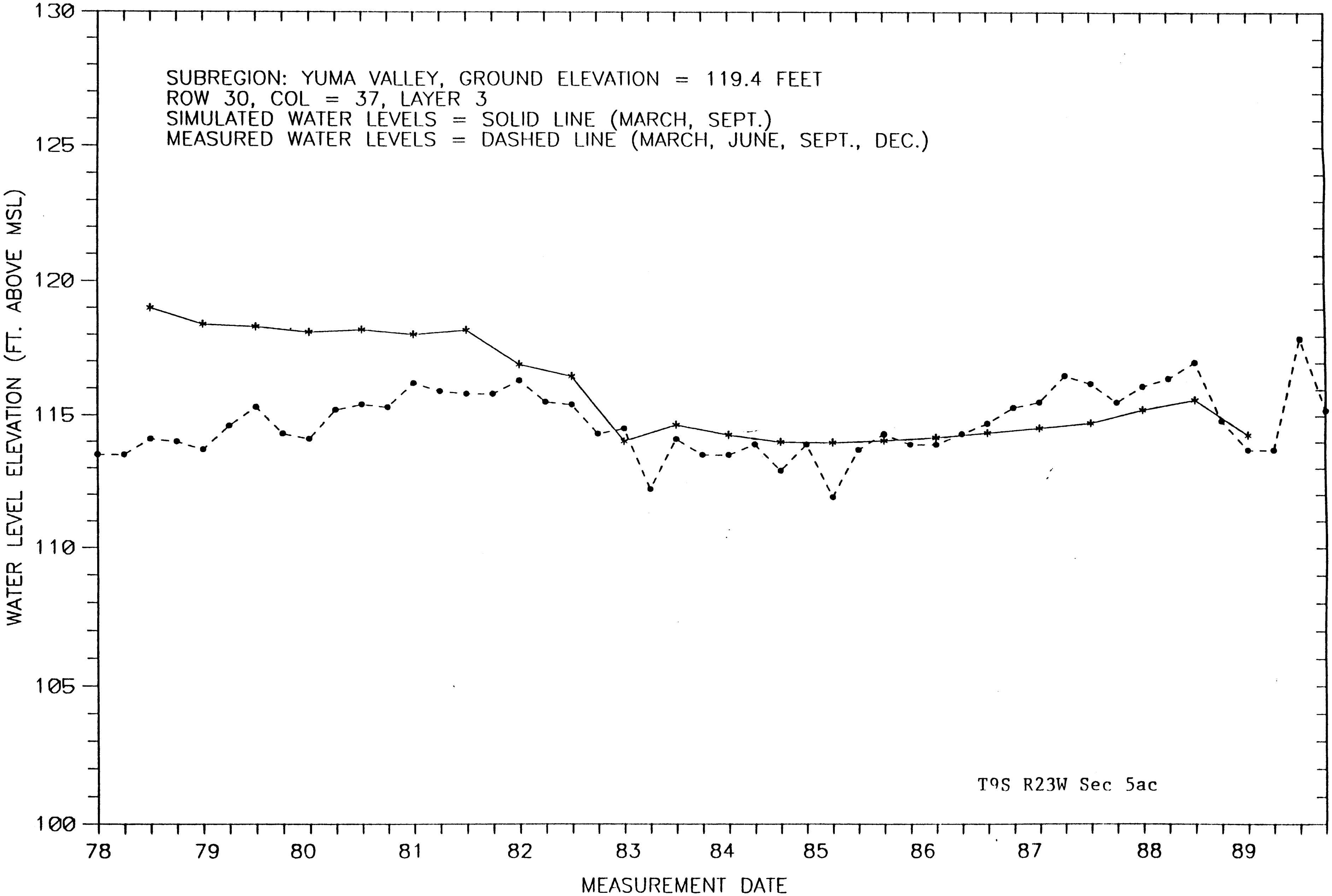
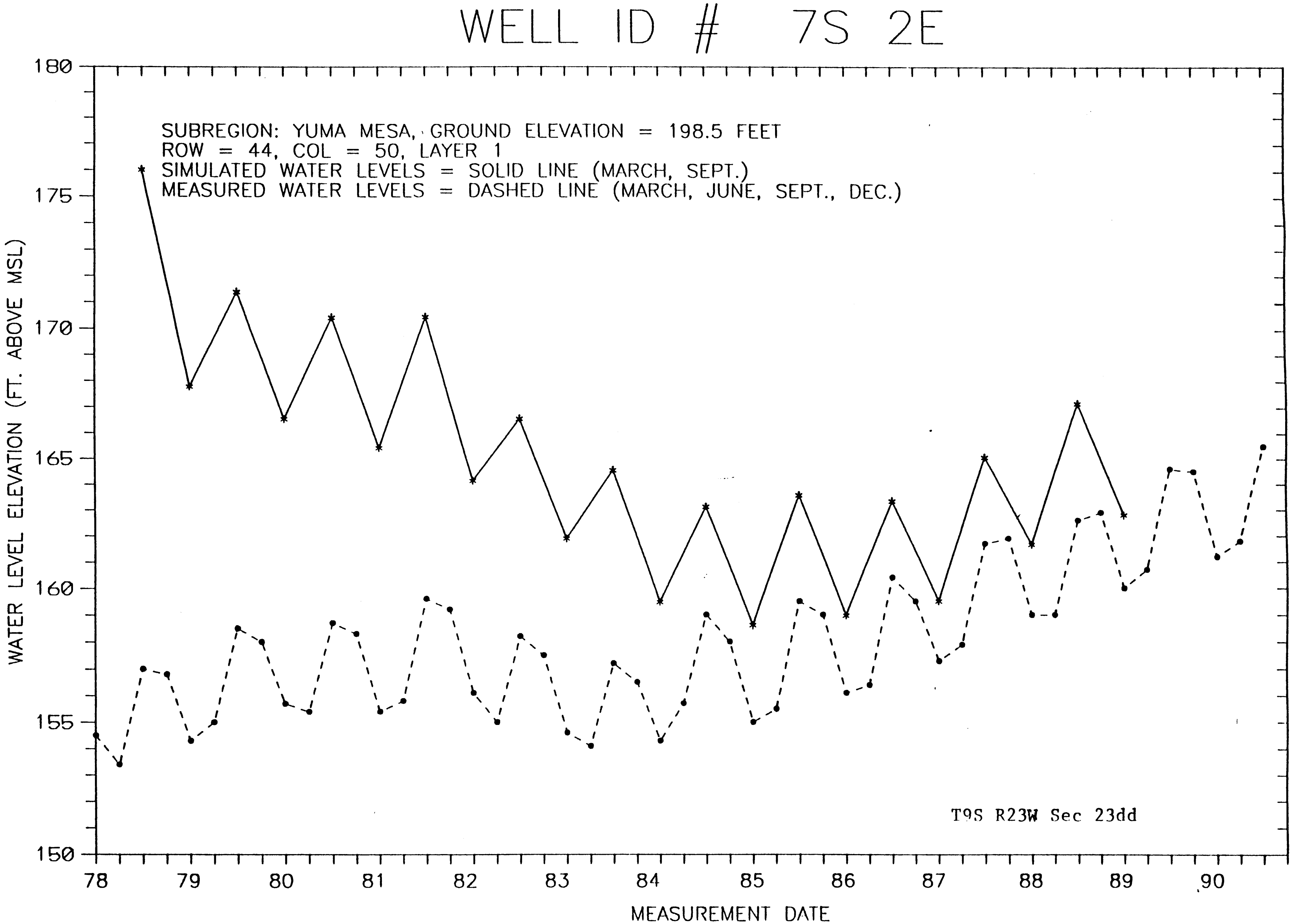
SUBREGION: YUMA VALLEY, GROUND ELEVATION = 96.5 FEET
ROW = 64, COL = 10, LAYER 3
SIMULATED WATER LEVELS = SOLID LINE (MARCH, SEPT.)
MEASURED WATER LEVELS = DASHED LINE (MARCH, JUNE, SEPT., DEC.)
WATER LEVEL ELEVATION (FT. ABOVE MSL)
100
95
90
85
80
75
70
78
79
80
81
82
83
84
85
86
87
88
89
MEASUREMENT DATE
T10S R25W Sec 14dd

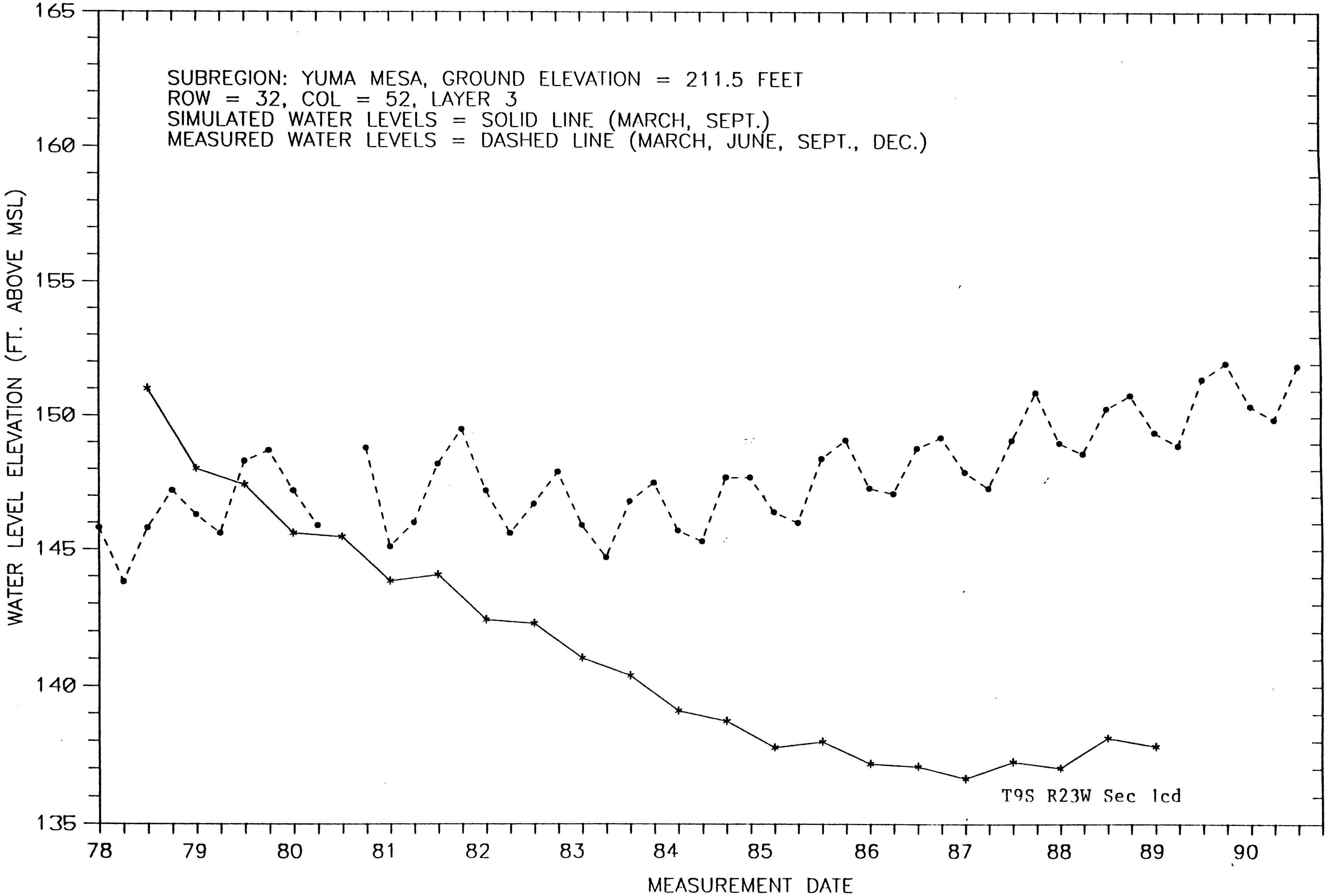
WELL ID # 3 1/2 S 1 1/2 W

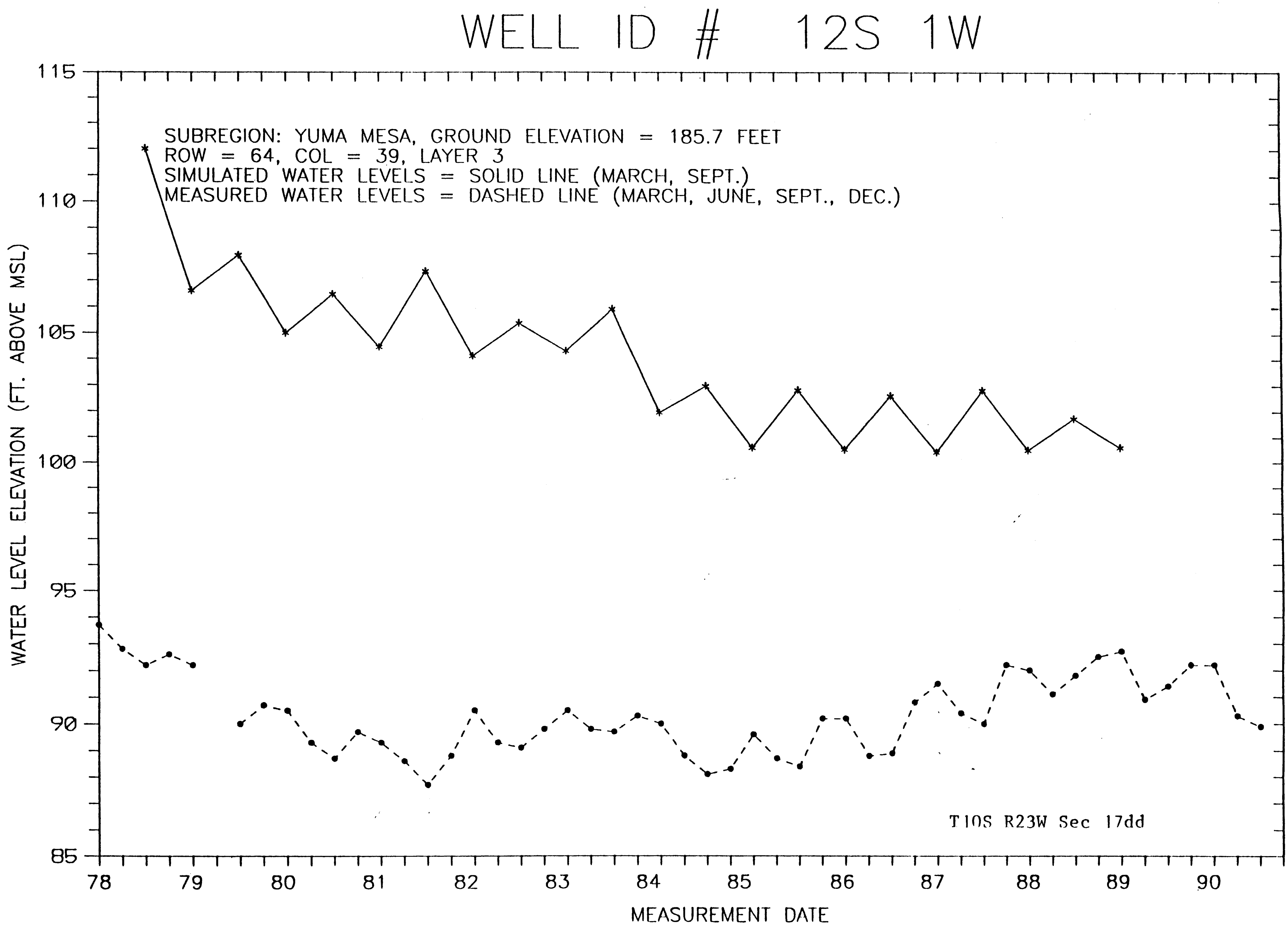




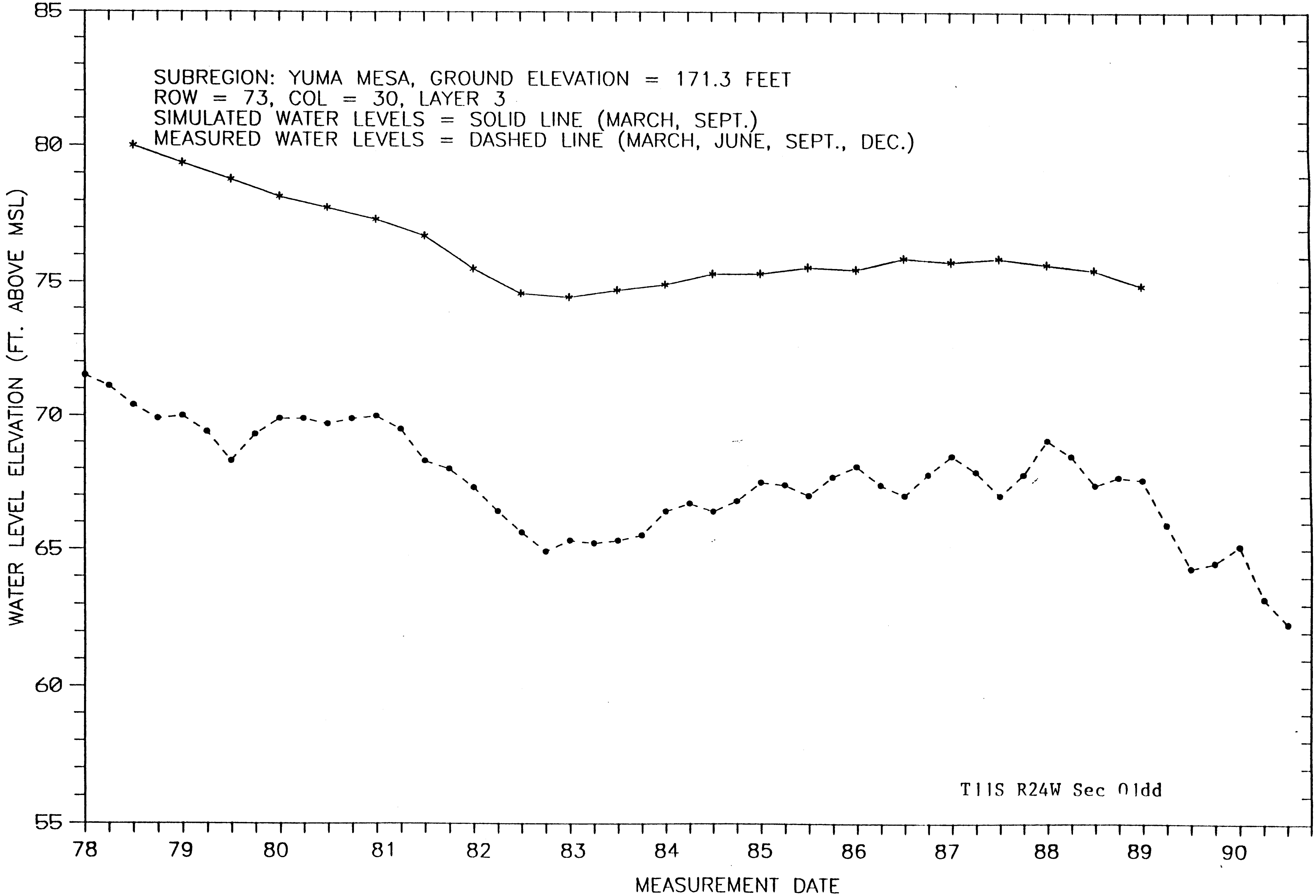
WELL ID # 7S 2E
SUBREGION: YUMA MESA, GROUND ELEVATION = 198.5 FEET
ROW = 44, COL = 50, LAYER 1
SIMULATED WATER LEVELS = SOLID LINE (MARCH, SEPT.)
MEASURED WATER LEVELS = DASHED LINE (MARCH, JUNE, SEPT., DEC.)
WATER LEVEL ELEVATION (FT. ABOVE MSL)
180
175
170
165
160
155
150
78
79
80
81
82
83
84
85
86
87
88
89
90
MEASUREMENT DATE
T9S R23W Sec 23dd

WELL ID # 4 S 2 1/2 E




WELL ID # 12S 1W
SUBREGION: YUMA MESA, GROUND ELEVATION = 185.7 FEET
ROW = 64, COL = 39, LAYER 3
SIMULATED WATER LEVELS = SOLID LINE (MARCH, SEPT.)
MEASURED WATER LEVELS = DASHED LINE (MARCH, JUNE, SEPT., DEC.)
WATER LEVEL ELEVATION (FT. ABOVE MSL)
115
110
105
100
95
90
85
78
79
80
81
82
83
84
85
86
87
88
89
90
MEASUREMENT DATE
T10S R23W Sec 17dd

WELL ID # 16S 3W



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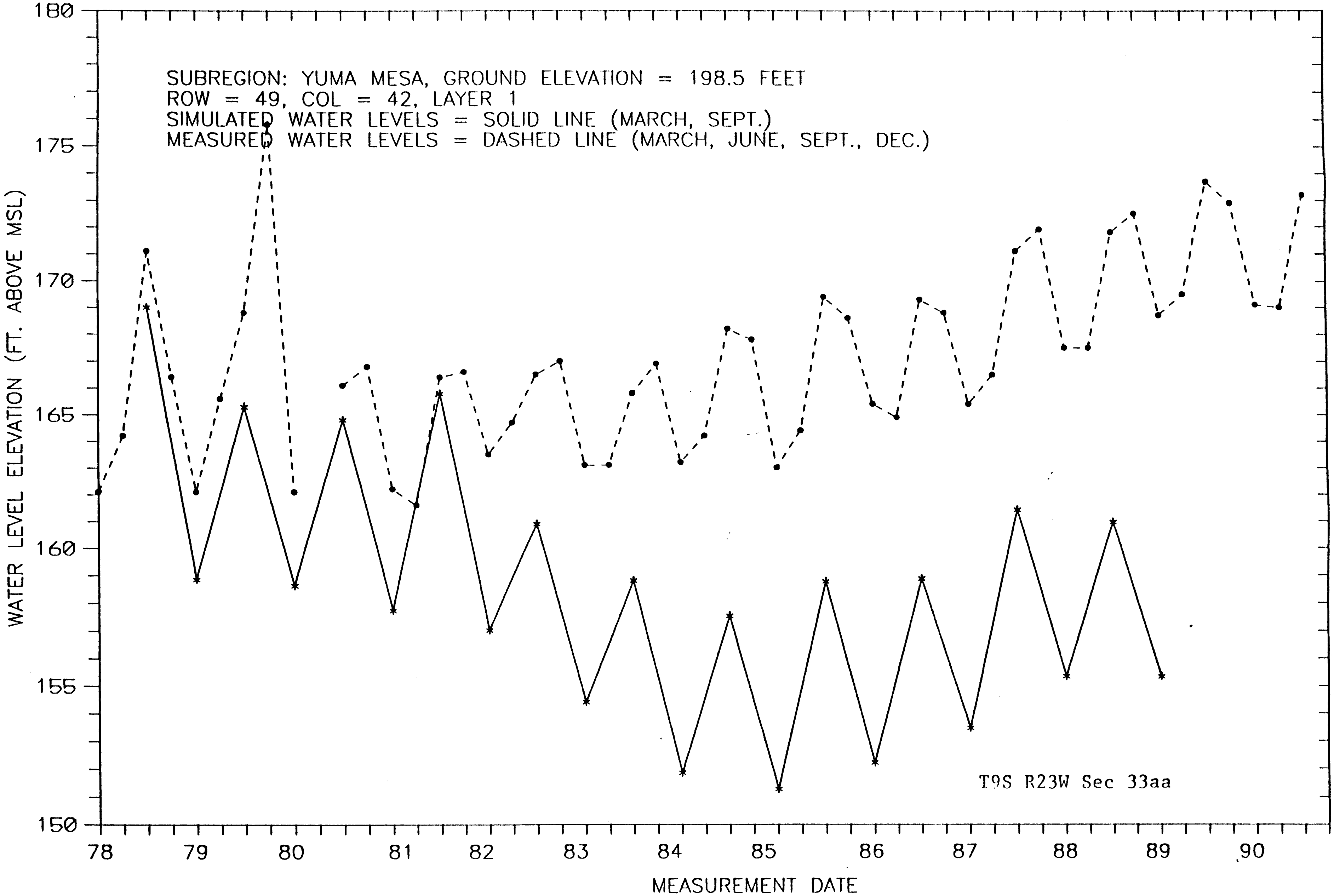
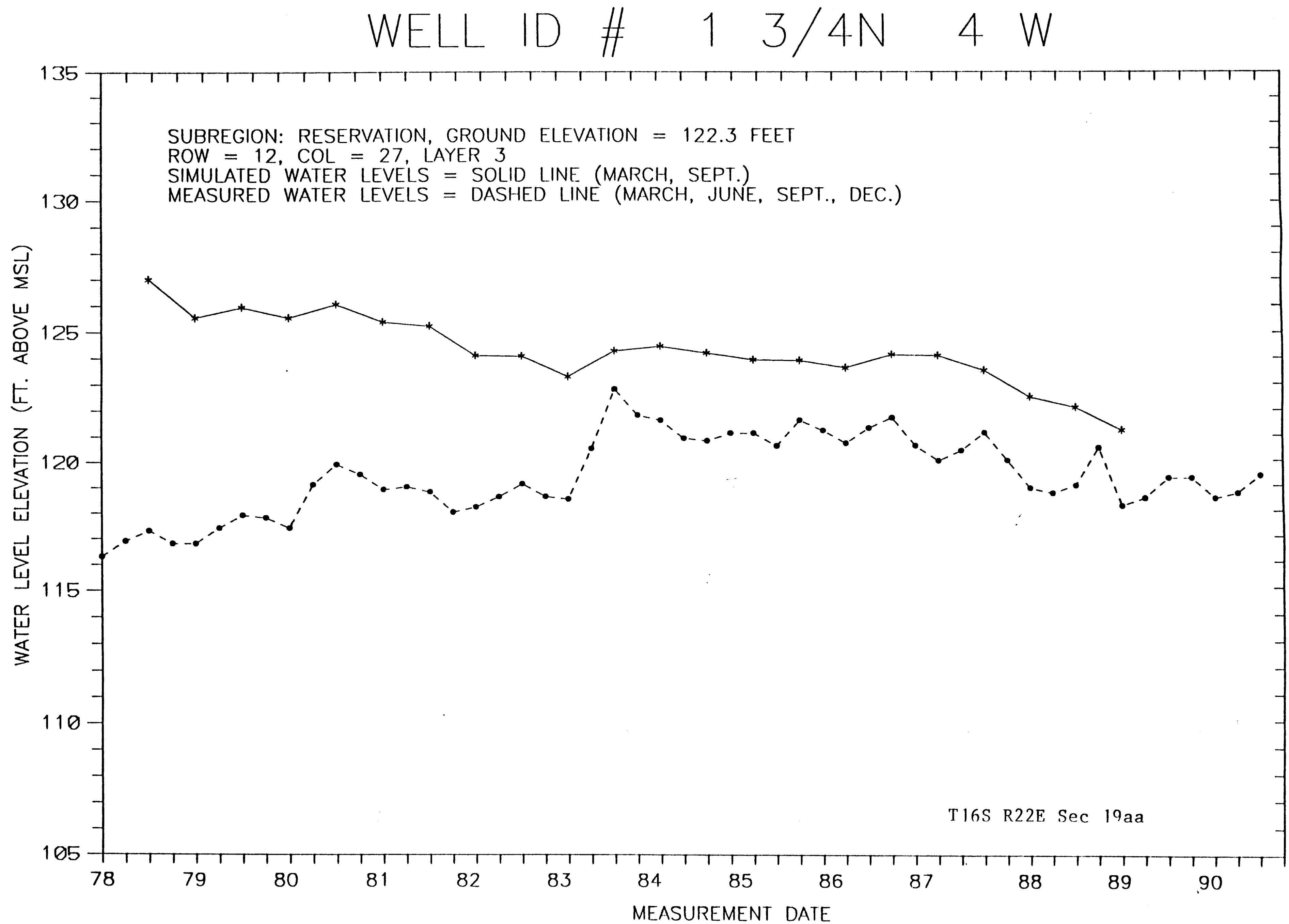
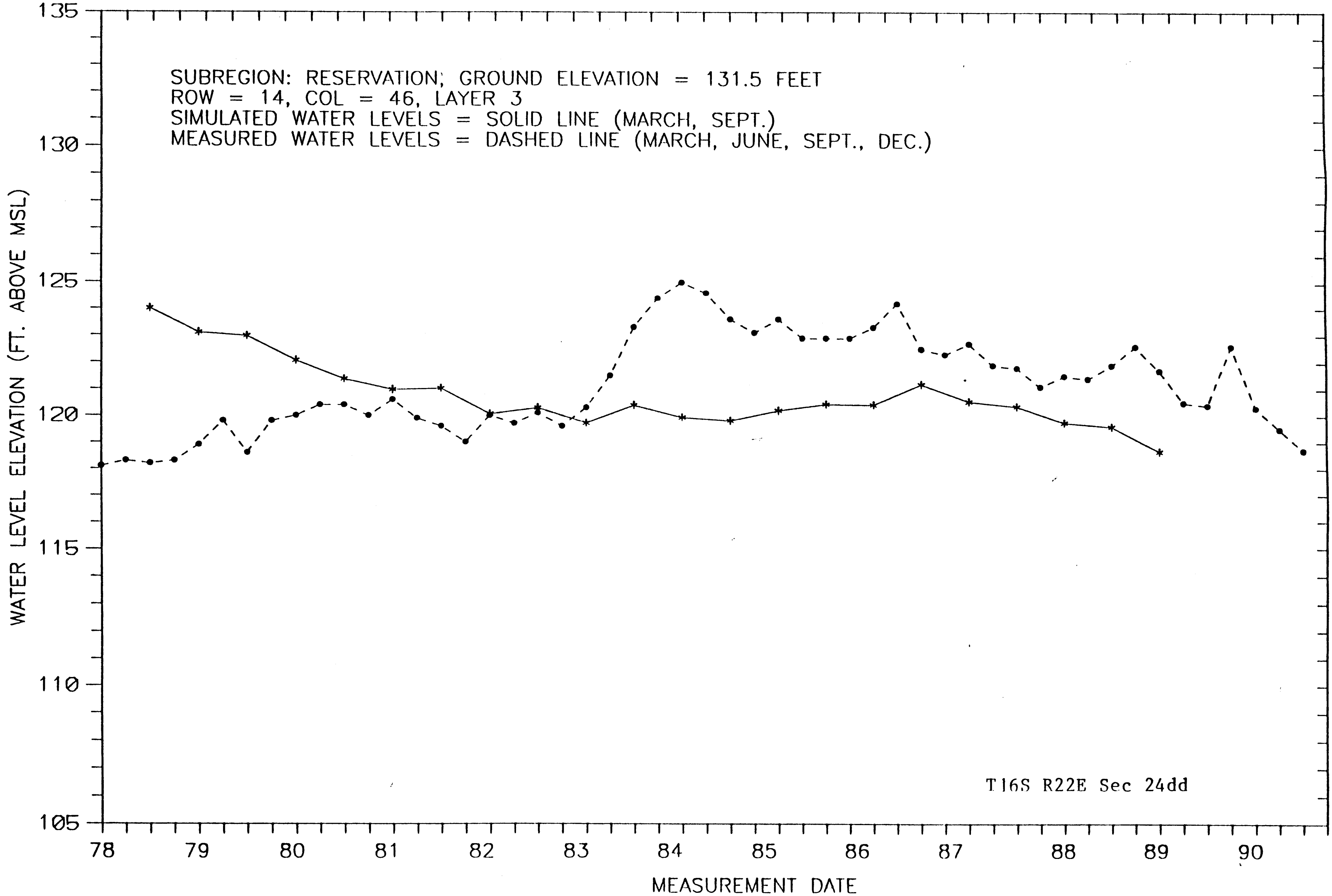
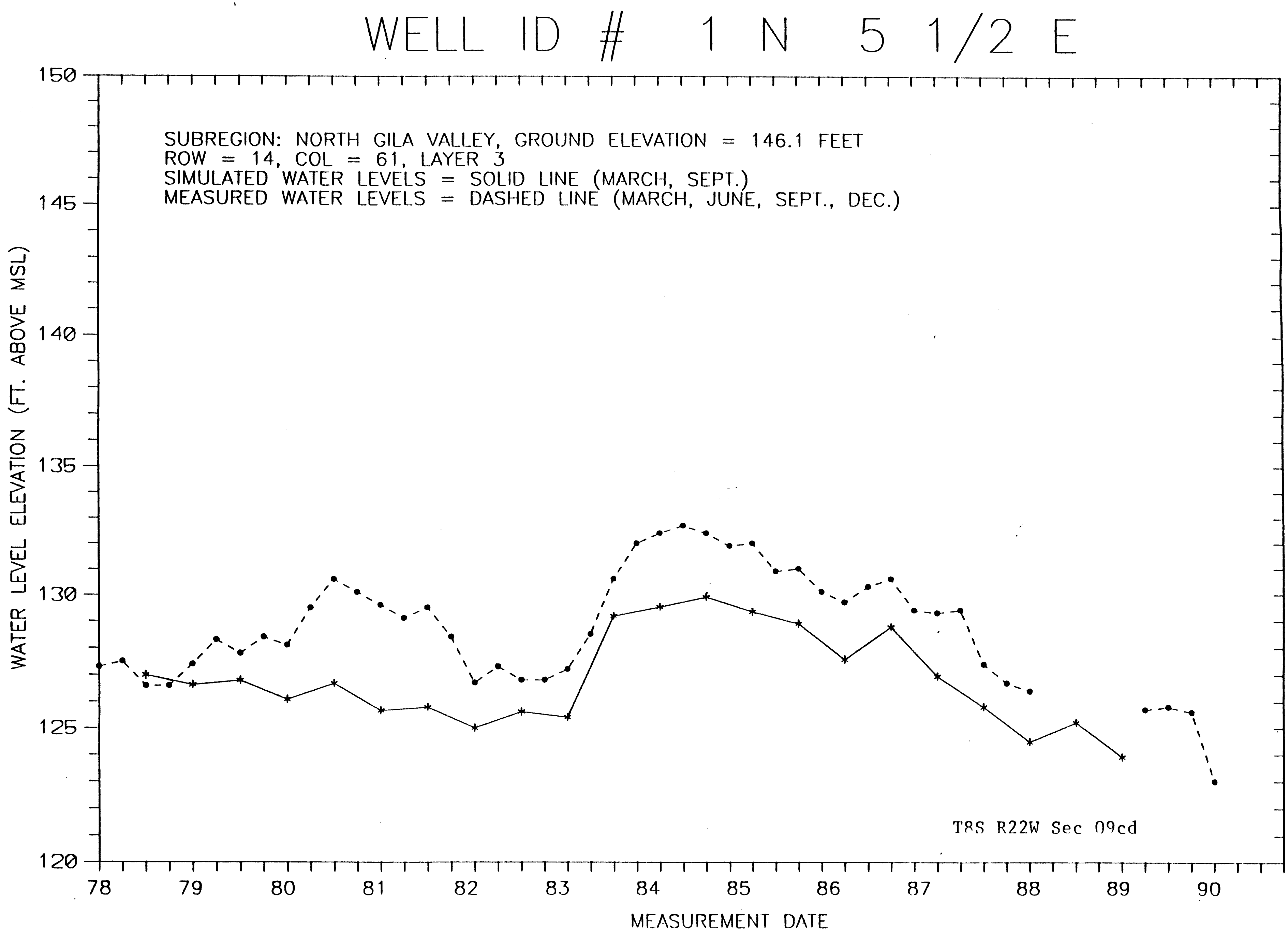



WELL ID # 1 3/4N 4 W
SUBREGION: RESERVATION, GROUND ELEVATION = 122.3 FEET
ROW = 12, COL = 27, LAYER 3
SIMULATED WATER LEVELS = SOLID LINE (MARCH, SEPT.)
MEASURED WATER LEVELS = DASHED LINE (MARCH, JUNE, SEPT., DEC.)
WATER LEVEL ELEVATION (FT. ABOVE MSL)
135
130
125
120
115
110
105
78
79
80
81
82
83
84
85
86
87
88
89
90
MEASUREMENT DATE
T16S R22E Sec 19aa

WELL ID # 1 N 1 E

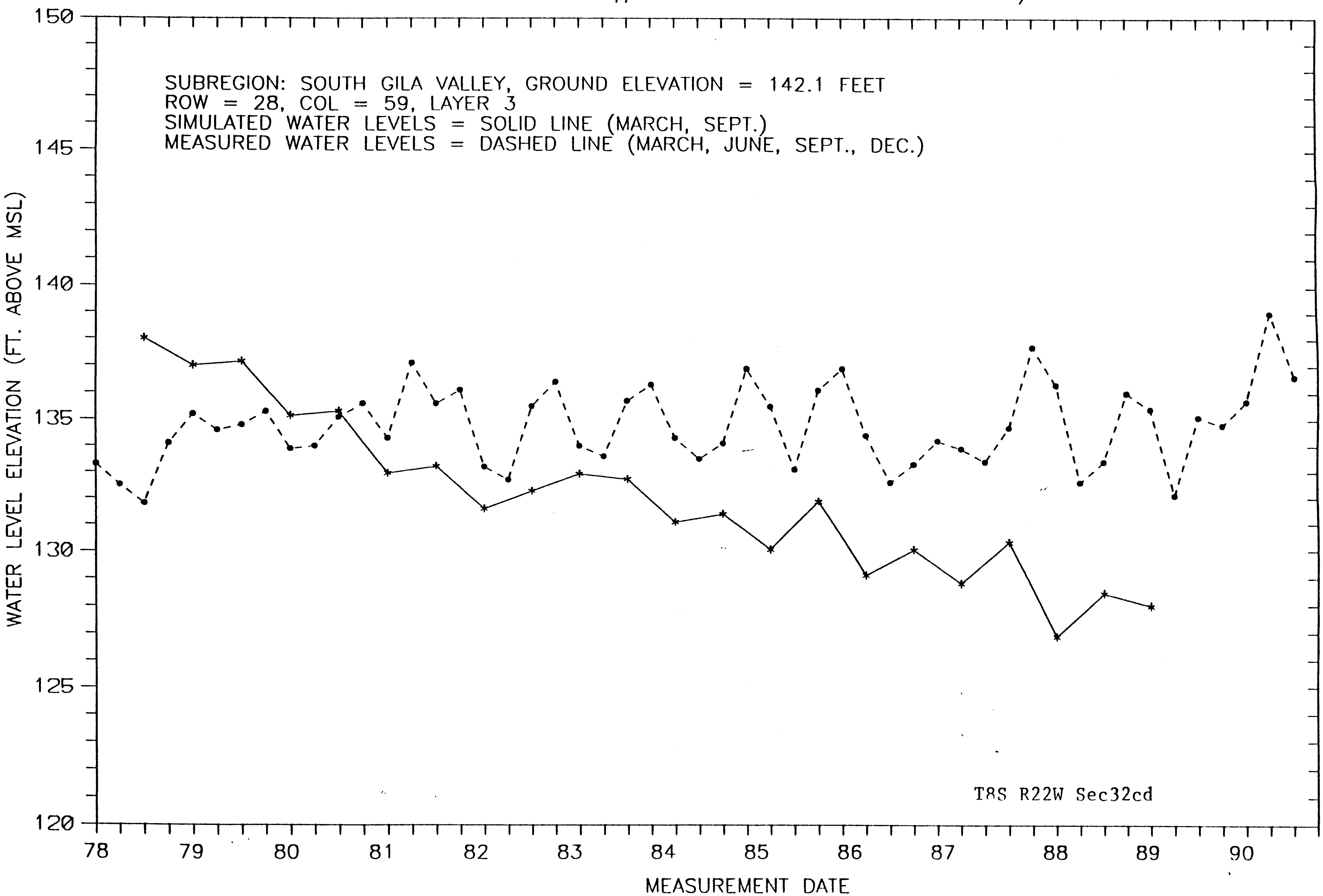


SUBREGION: RESERVATION; GROUND ELEVATION = 131.5 FEET
ROW = 14, COL = 46, LAYER 3
SIMULATED WATER LEVELS = SOLID LINE (MARCH, SEPT.)
MEASURED WATER LEVELS = DASHED LINE (MARCH, JUNE, SEPT., DEC.)
WATER LEVEL ELEVATION (FT. ABOVE MSL)
135
130
125
120
115
110
105
78
79
80
81
82
83
84
85
86
87
88
89
90
MEASUREMENT DATE
T16S R22E Sec 24dd



WELL ID # 1 N 5 1/2 E
SUBREGION: NORTH GILA VALLEY, GROUND ELEVATION = 146.1 FEET
ROW = 14, COL = 61, LAYER 3
SIMULATED WATER LEVELS = SOLID LINE (MARCH, SEPT.)
MEASURED WATER LEVELS = DASHED LINE (MARCH, JUNE, SEPT., DEC.)
WATER LEVEL ELEVATION (FT. ABOVE MSL)
150
145
140
135
130
125
120
78
79
80
81
82
83
84
85
86
87
88
89
90
MEASUREMENT DATE
T8S R22W Sec 09cd

WELL ID # 3 S - 4 1/2 E

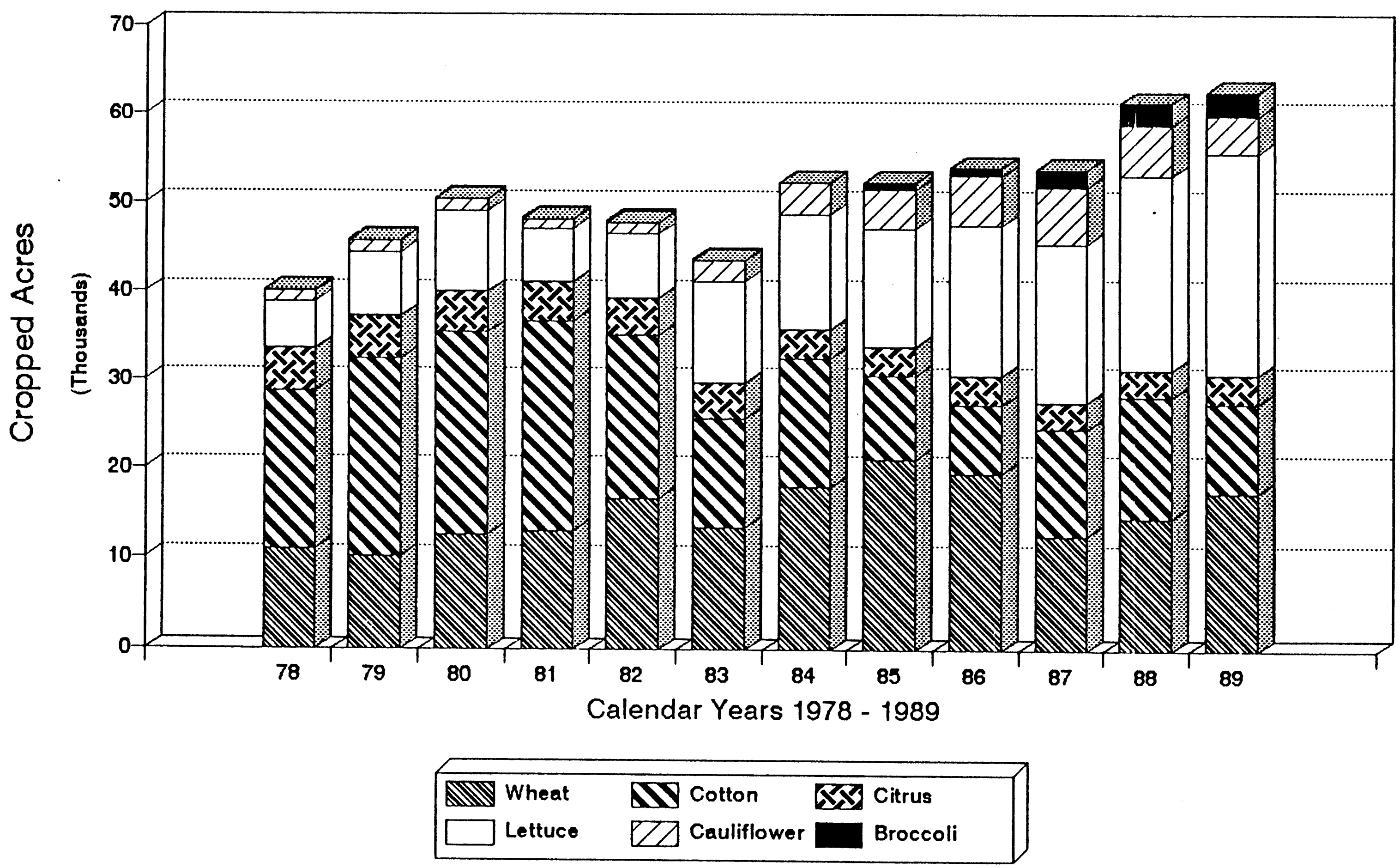


APPENDIX IV SCENARIO SIMULATION FIGURES

TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE YUMA VALLEY SUBAREA

Figure 16

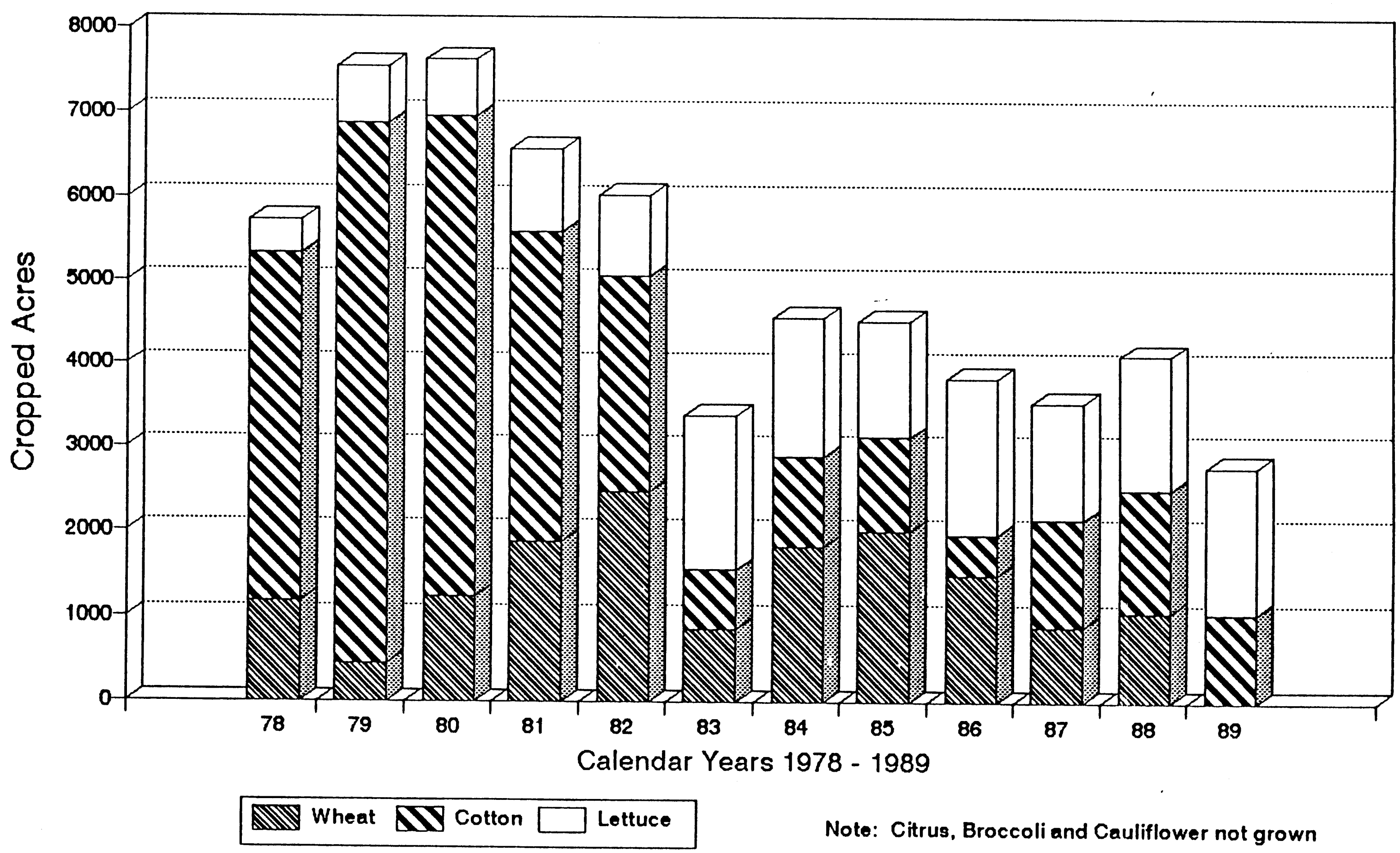
Yuma County Water Users Association



TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE RESERVATION SUBAREA

Figure 17

Reservation Irrigation District

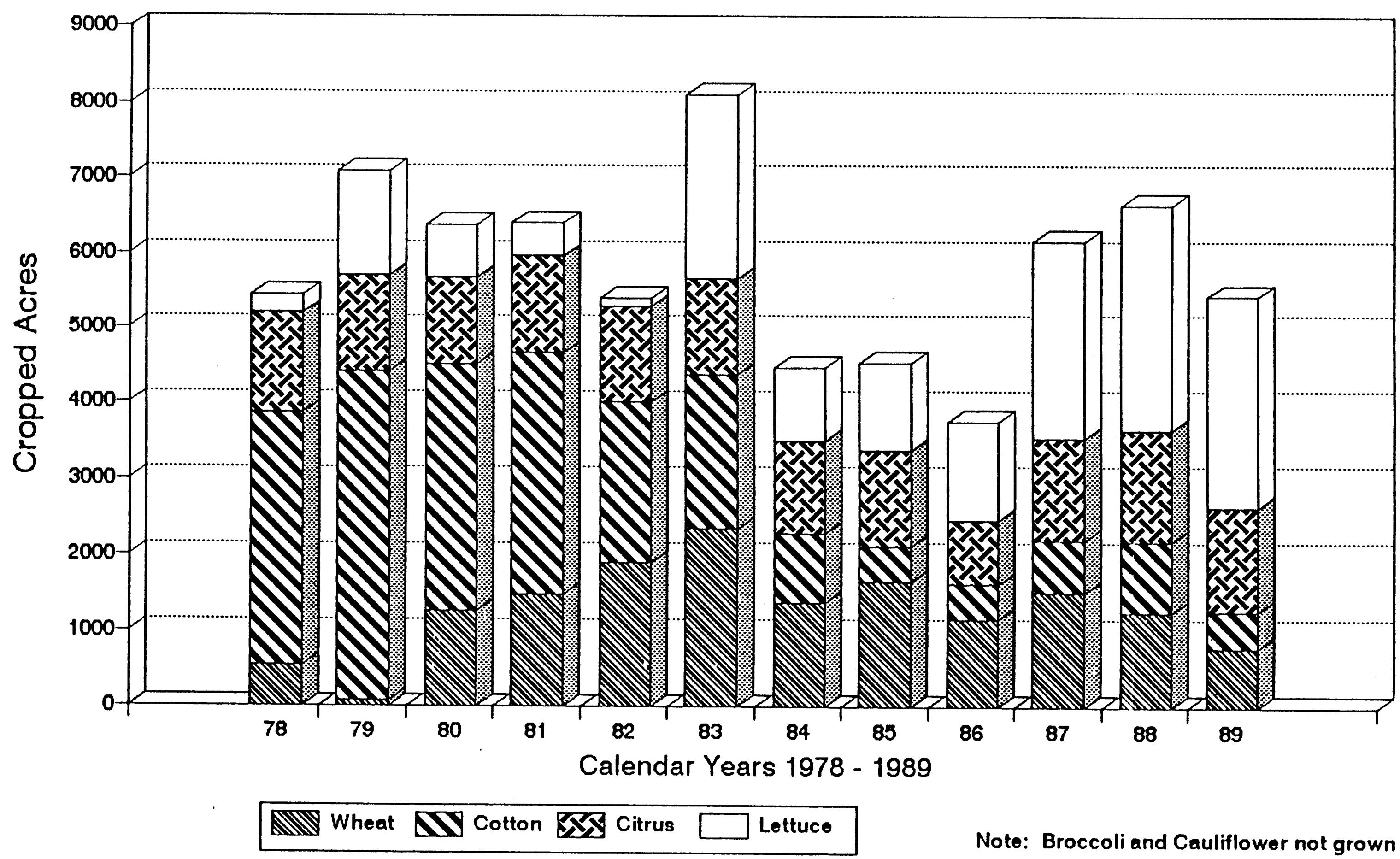


Note: Citrus, Broccoli and Cauliflower not grown

TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE RESERVATION SUBAREA

Figure 18

Bard Irrigation District

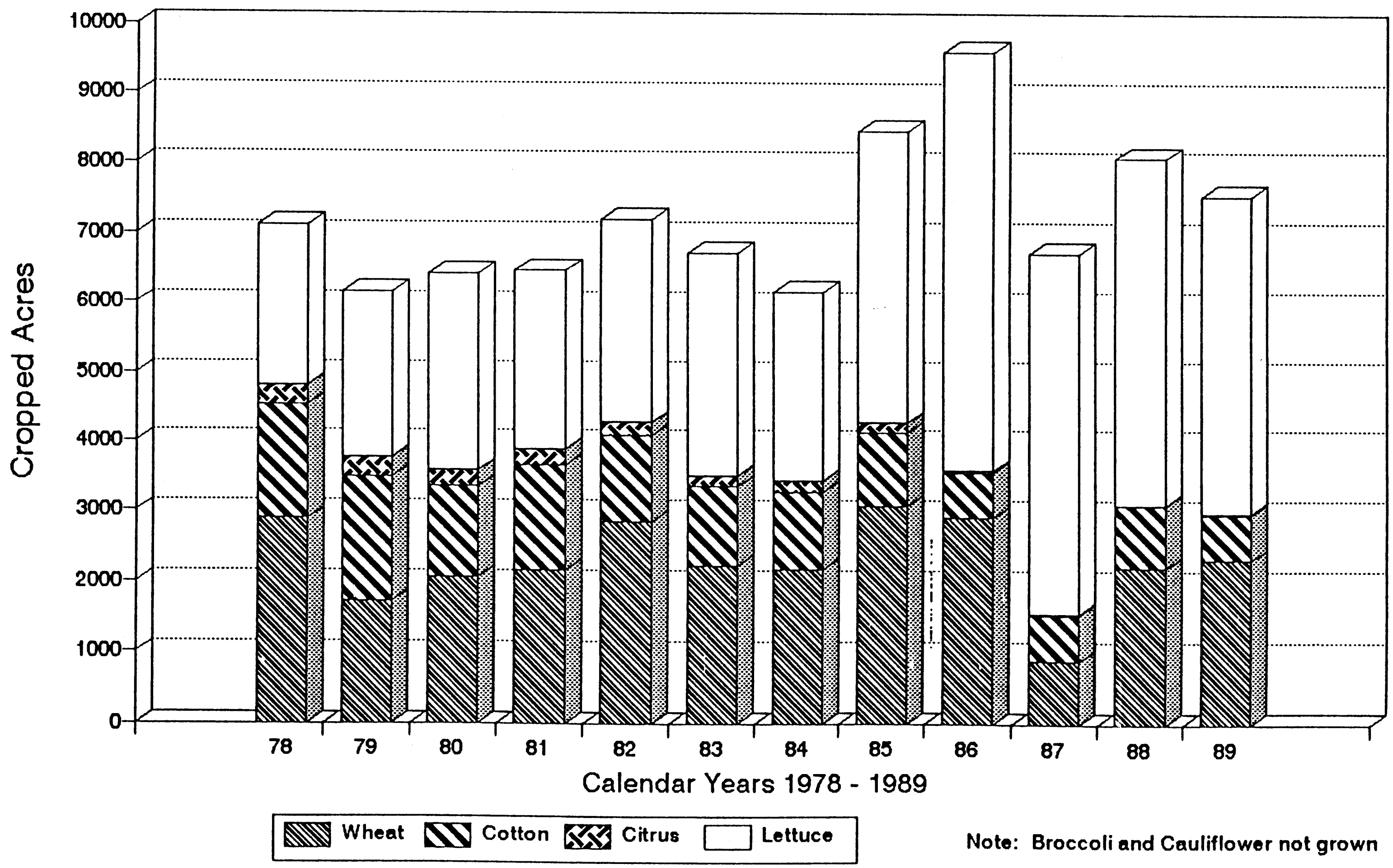


Note: Broccoli and Cauliflower not grown

Figure 19

TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE NORTH GILA VALLEY SUBAREA

North Gila Valley Irrigation District

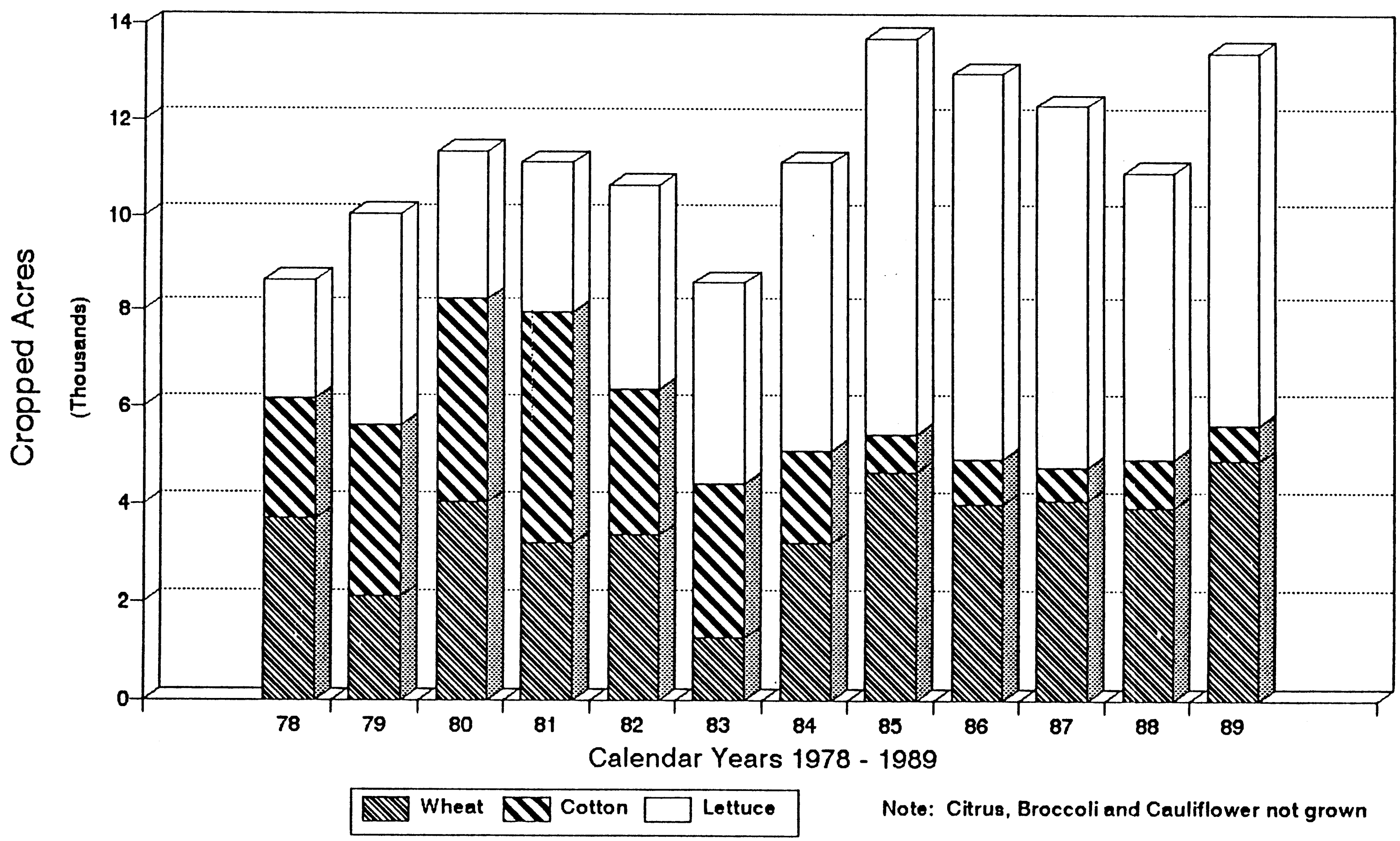


Note: Broccoli and Cauliflower not grown

TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE SOUTH GILA VALLEY SUBAREA

Figure 20

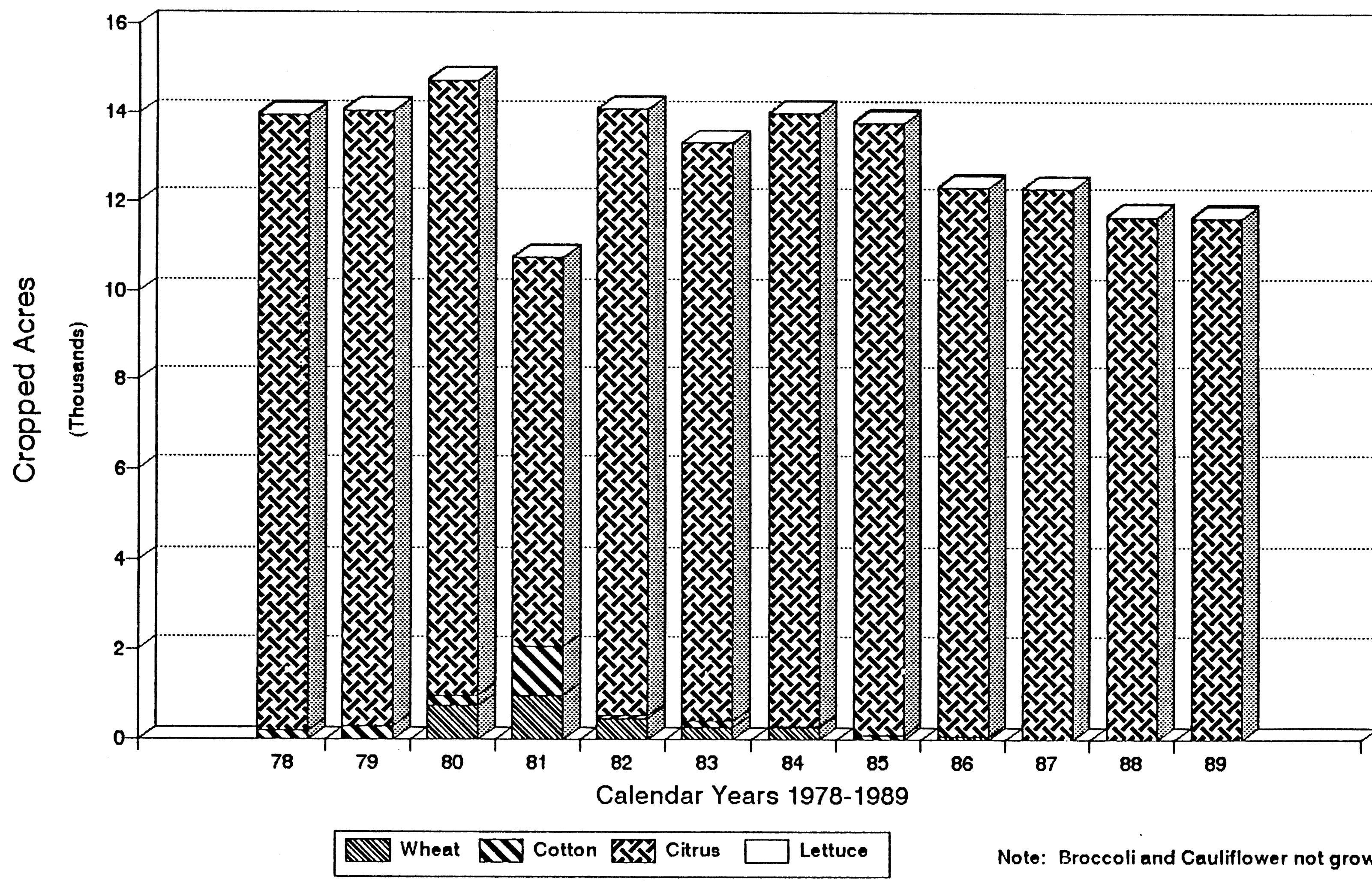
Yuma Irrigation District



TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE YUMA MESA SUBAREA

Figure 21

Yuma Mesa Irrigation District

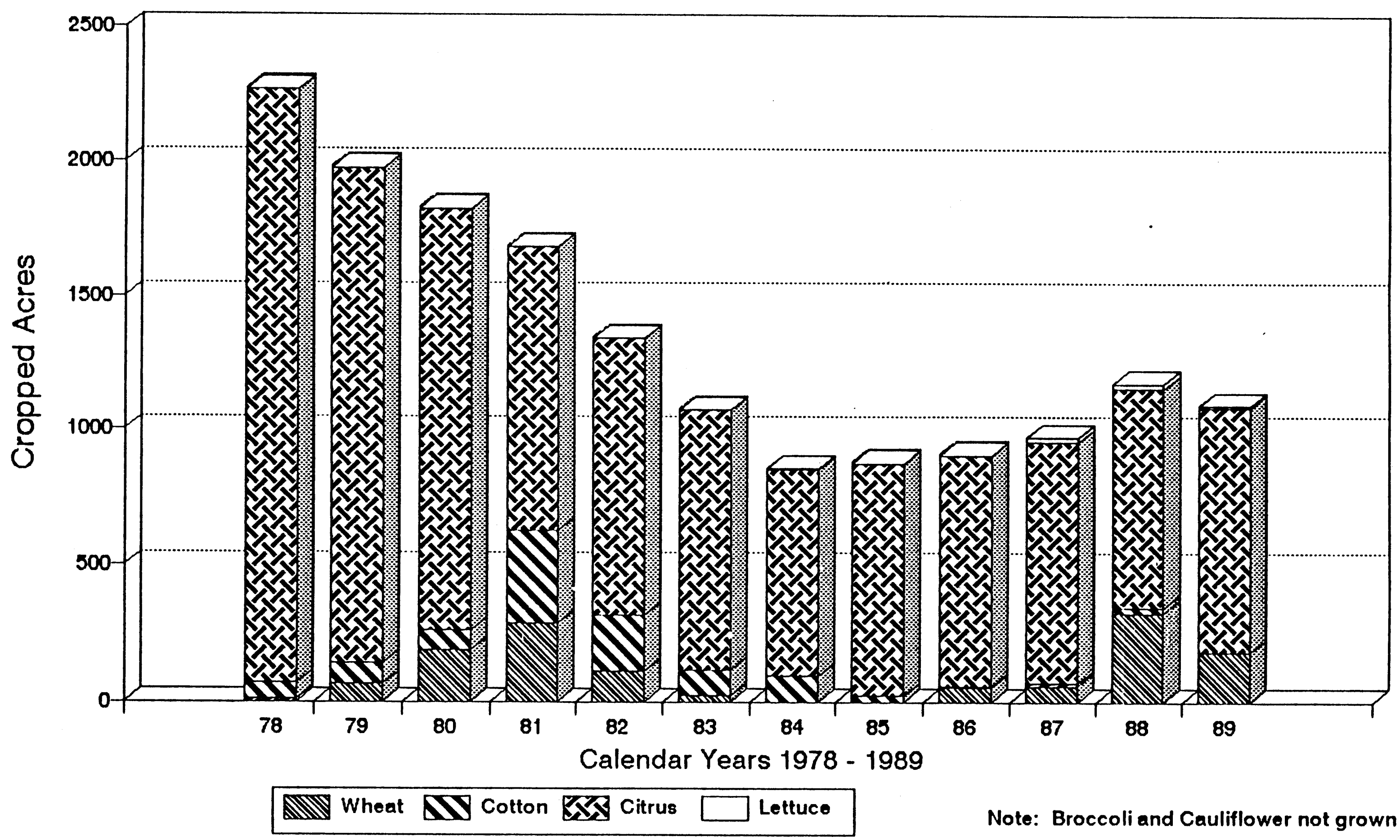


Note: Broccoli and Cauliflower not grown

TOTAL ANNUAL ACREAGE FOR SELECTED CROP TYPES FOR THE YUMA MESA SUBAREA

Unit B.I.D.D.

Figure 22

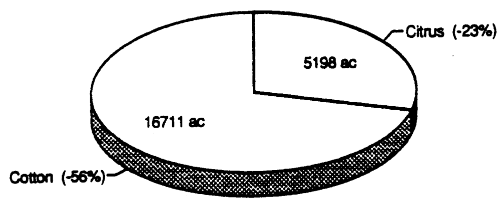


Note: Broccoli and Cauliflower not grown

PERCENT DECREASE AND INCREASE IN TOTAL ACRES FOR SELECTED CROPS BETWEEN 1978 AND 1989 FOR ALL IRRIGATION DISTRICTS

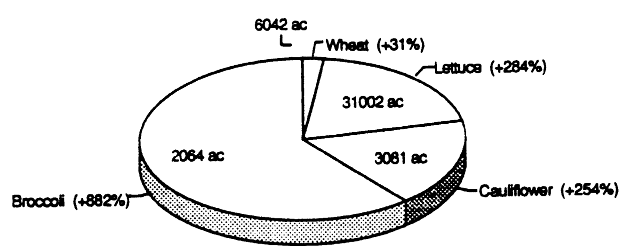
FIGURE 23

PERCENT DECREASE IN TOTAL ACRES FOR SELECTED CROPS BETWEEN 1978 AND 1989 FOR ALL IRRIGATION DISTRICTS IN THE YUMA AREA
USA ONLY



Note: -56% = % decrease in cropped acres between 1978 and 1989
16711 = total cropped acre decrease

PERCENT INCREASE IN TOTAL ACRES FOR SELECTED CROPS BETWEEN 1978 AND 1989 FOR ALL IRRIGATION DISTRICTS IN THE YUMA AREA
USA ONLY



Note: +882% = % increase in cropped acres between 1979 and 1989
2064 = total cropped acre increase

FIGURE 27. FLOW IN COLORADO RIVER AT LAGUNA DAM (Gage 09429600)

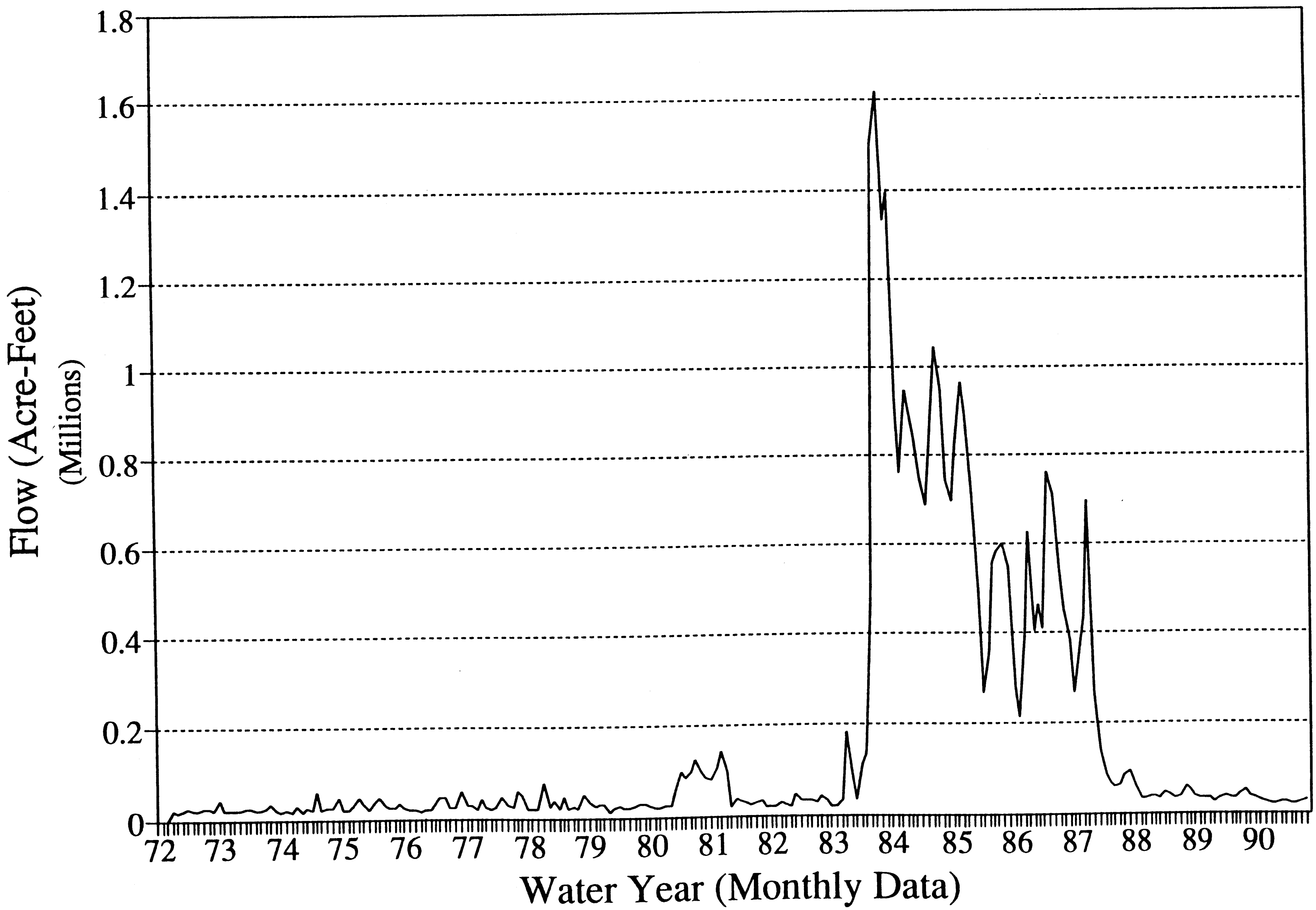


FIGURE 28. FLOW IN GILA RIVER NEAR DOME, AZ (Gage 09520500)