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Development of a Numerical Ground-Water Flow Model

and

Assessment of Ground-Water Basin Yield

Santa Maria Valley Ground-Water Basin

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prepared for

Santa Maria Valley Water Conservation District

March, 2000

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CONSULTING ENGINEERS

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by

Luhdorff and Scalmanini
Consulting Engineers

March, 2000

99-1-034

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I. Executive Summary

As part of its ongoing ground-water management work in the Santa Maria Valley, the Santa Maria Valley Water Conservation District commissioned the preparation of a numerical ground-water flow model to be used for assessment of ground-water basin conditions and for evaluation of existing and/or future projects and land use conditions in the basin. A primary initial purpose of model development was to assess the perennial yield and current state of the basin, whether it was developed within perennial yield or, if not, whether it was in overdraft. The ground-water flow model has been completed and can now be used to provide input to the various ongoing water resource management activities of the District.

In the preparation of the ground-water model, the objectives were to: 1) develop an understanding of the hydrogeology of the greater part of the Santa Maria ground-water basin (study area); 2) develop and calibrate a numerical ground-water flow model of the study area; 3) formulate possible model scenarios for predicting the impacts on ground-water levels of different management actions taken by the District or other entities within the study area: and 4) utilize the calibrated model results, specifically the simulated historical conditions during an established base study period, to estimate the yield and current state of the basin.

The study area encompasses a majority of the Santa Maria ground-water basin, a coastal basin approximately 250 square miles in size located within northern Santa Barbara and southern San Luis Obispo Counties. The study area includes that portion of the basin of greatest significance to the District: specifically, the contiguous area of the Santa Maria Valley, Sisquoc plain, Orcutt upland, and the approximate southern half of the Nipomo Mesa (south of Black Lake Canyon). It encompasses areas, within and adjoining the District boundaries, comprised primarily of agricultural land and areas of native vegetation. The study area also includes the urban areas of Santa Maria, Guadalupe, Orcutt, and Nipomo, as well as several small developments and industrial areas. The main stream in the study area is the Santa Maria River, which generally flanks the northern part of the Santa Maria Valley; other streams include portions of the Cuyama River, Sisquoc River and tributaries, and Orcutt Creek.

For the initial part of model development and basin assessment, the geology of the study area was defined, including the nature and extent of the geologic formations comprising the aquifer system and the geologic structure of the basin. The hydrology of the study area was characterized, including determining the historical trends in ground-water level fluctuations, historical ground-water flow patterns, and historical trends in streamflow and precipitation. In addition, the distribution of hydraulic characteristics of the various aquifers and the nature of the surface-water: aquifer interaction was defined.

A numerical ground-water flow model has been developed using the U.S. Geological Survey's MODFLOW modeling code encompassing the entire ground-water basin (with the active portion of the model comprising the study area) and including all of the basin aquifers. The model simulates transient conditions during the 53-year period between 1944 and 1997 and incorporates the historical hydraulic stresses within the basin; these include the recharge of streamflow, precipitation, and irrigation and M&I return flows, and the discharge from agricultural and M&I pumpage and evapotranspiration losses. The model was calibrated by adjusting certain model input parameters until the model-simulated hydraulic head (ground-water levels) matched actual observed ground-water levels as closely as possible.

Several model scenarios have been formulated to illustrate potential applications of the model in the overall planning and management of water resources in the basin. These scenarios include simulations of historical conditions within the basin and of alternative conditions during the historical period (for example, the ground-water conditions that would have resulted without the Twitchell project). Additional scenarios that could be simulated for water supply planning purposes include predictive simulations of future conditions that would examine the ability of the basin to support future demands for agricultural and/or M&I water supply.

The calibrated ground-water model has been utilized to assess historical conditions in the basin during an established base study period, specifically the 22 year period from 1968 to 1989, in order to develop a value for the perennial yield of the basin within the study area. The selected base period for assessment of perennial yield encompasses a time through which there was an average amount of natural recharge, and when there was no unbalanced storage in the unsaturated zone between the ~~beginning~~ ~~and~~ ~~end~~ ~~of~~ the period. The base period also includes varying stress periods (wet and dry periods), and is in reasonable proximity to the present. Based on interpretation of ground-water levels and no changes in model-calculated ground-water storage over the study period, basin conditions are concluded to be within perennial yield and not in overdraft. The average pumpage for all beneficial uses in the study area during this period was 124,000 acre-feet, and this quantity can be interpreted as the perennial yield of the basin under current distribution of pumpage, land use, and associated return flows, with continued augmentation of ground-water recharge from the Twitchell project, and under conditions of long-term average precipitation. Finally, consistent with the observation of development within perennial yield in the basin, it was also concluded that a substantial amount of aquifer storage can intermittently be used to sustain water supply during periodic dry periods, as has been the case in the basin on several occasions in the last 50 years, without resulting in perennial deficit or decline in ground-water levels or storage.

II. Introduction

Purpose and Scope

With the adoption of a ground-water management plan in 1995, under the general authority granted by AB 3030, the Santa Maria Valley Water Conservation District (the District) embarked on an updated program to continue to manage ground-water resources within portions of the Santa Maria basin. Prior to adoption of a formal ground-water management plan, the District had for years been involved in ground-water management, primarily via the operation of Twitchell Dam and Reservoir for artificial recharge of ground water through the downstream river channel. Basin management requires an understanding of the impacts on ground-water levels and storage that could result from any management actions taken by the District or other entities within the basin. In addition, a clear understanding of the ground-water resources within the basin and the status of the ground-water basin are important inputs to water rights considerations in the basin, particularly in an era of changing municipal water demands and supplies, as well as potentially expanding agricultural land use within and adjacent to the basin. In order to provide input to these processes and at the request of the District, Luhdorff and Scalmanini, Consulting Engineers have developed a ground-water flow model of the greater portion of the Santa Maria basin.

For purposes of this report, the ground-water flow model was used to simulate the response of the basin (that portion within the study area) to the recent historical conditions, specifically from 1944 to 1997. This included the historical climatic conditions and land use and the associated changes in inflows to and outflows from the study area. In addition, the model was used to calculate the changes in storage during selected periods of time to provide an estimate of the perennial yield of the aquifer system, and to provide an assessment of whether pumping in the basin is within perennial yield or, if not, whether the basin is in overdraft.

This report describes the hydrogeologic conditions present in the area, the development of the model, and the application of the model to assess basin conditions (storage and yield estimates). The report is organized as follows:

Chapter I.	Executive Summary
Chapter II.	Introduction
Chapter III.	Hydrogeologic Conditions
Chapter IV.	Ground-Water Flow Model
Chapter V.	Model Applications and Basin Yield

Description of Study Area

The study area encompasses a majority of the Santa Maria ground-water basin, a coastal basin located within northern Santa Barbara and southern San Luis Obispo Counties, including the Santa Maria Valley, Sisquoc plain, Orcutt upland, and the approximate southern half of the Nipomo Mesa (south of Black Lake Canyon) (Figure 2-1). It includes areas within and adjoining the District boundaries comprised primarily of agricultural land and areas of native vegetation. The study area also includes the urban areas of Santa Maria, Guadalupe, Orcutt, and Nipomo, as well as several small developments and industrial areas. The main stream in the study area is the Santa Maria River, which generally flanks the northern part of the Santa Maria Valley; other streams include portions of the Cuyama River, Sisquoc River and tributaries, and Orcutt Creek.

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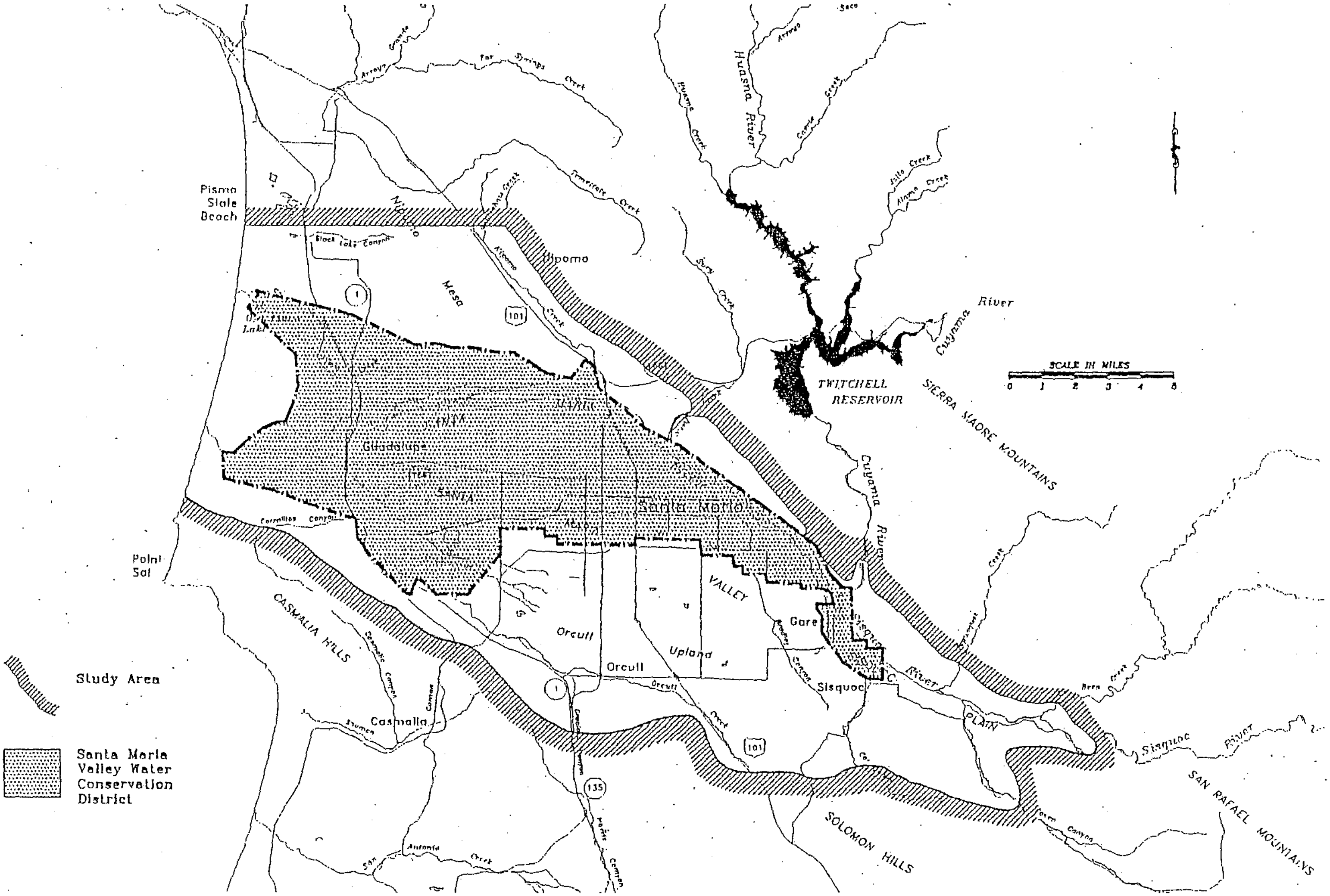

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Figure 2-1
Study Area and District Boundaries
Santa Maria Ground-Water Basin

III. Hydrogeologic Conditions

The Santa Maria ground-water basin includes approximately 250 square miles comprised of river bed, alluvial plain, and upland (mesa) areas within Santa Barbara and San Luis Obispo Counties. The study area encompasses a majority of the basin, and specifically that portion of greatest significance to the District: the contiguous area of the Santa Maria Valley, Sisquoc plain, Orcutt upland, and the portion of the Nipomo Mesa south of Black Lake Canyon (Figure 3-1). Surrounding the study area are the Casmalia and Solomon Hills to the south, the San Rafael Mountains to the southeast, the Sierra Madre Mountains to the east and northeast, the remaining portion of the Nipomo Mesa to the north, and the Pacific Ocean to the west. The study area is drained mainly by the Santa Maria River, with inflow from the Cuyama and Sisquoc Rivers and several minor tributaries. The basin boundary designations (historical and current) and the study area geology and hydrology are described in the following subsections.

Basin Boundary

The boundary of the ground-water basin has previously been designated based on geologic and hydrologic conditions, as discussed below. There is currently general agreement on the western, southern, and eastern boundaries, but some open question regarding the northern boundary. All but the northern boundary have historically been designated as the contact of fresh water-bearing alluvial deposits of the Santa Maria Valley with essentially non-fresh water-bearing consolidated deposits comprising the surrounding hills and mountains (see Figure 3-1).

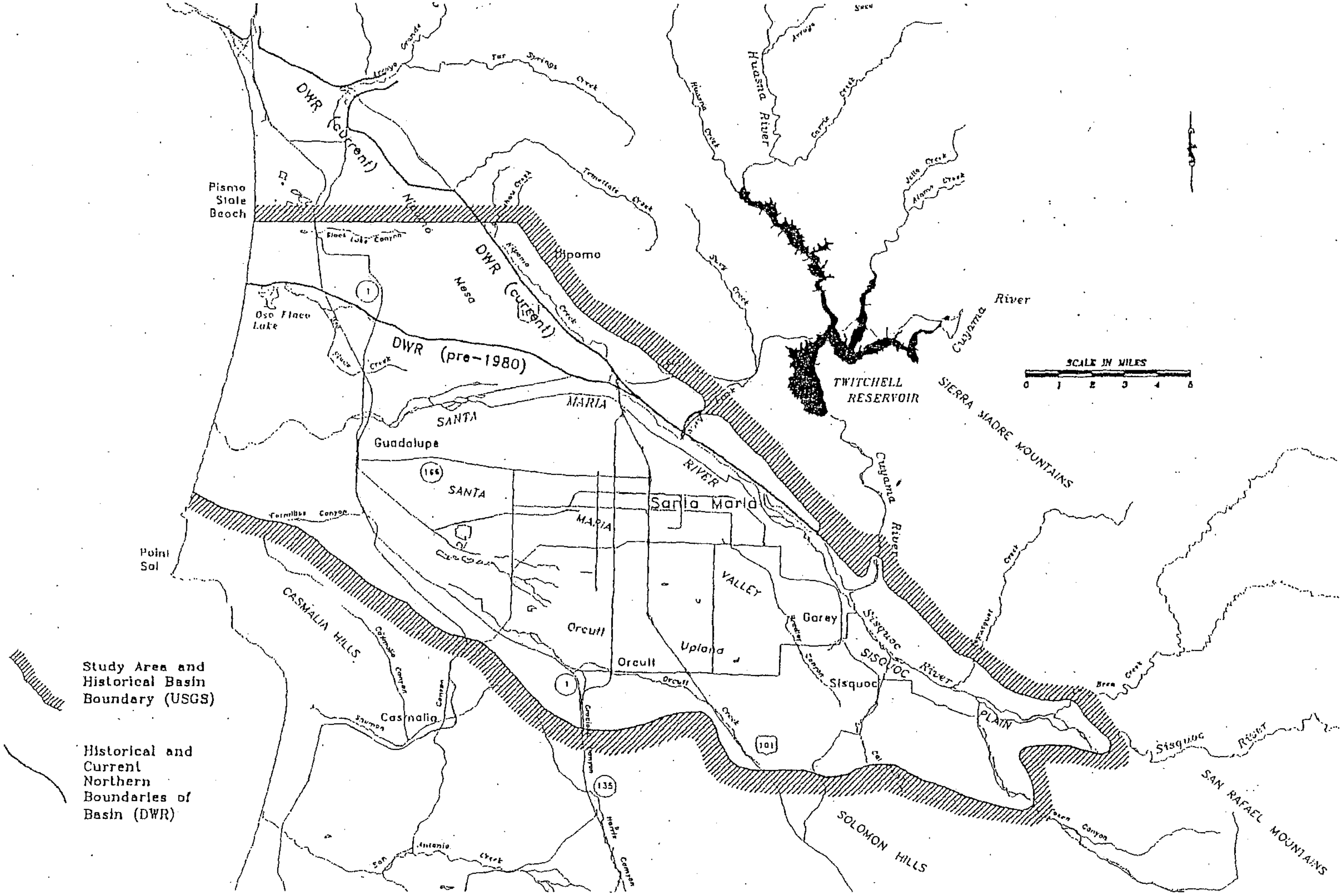

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Figure 3-1
Study Area and Historical Basin Boundary Designations
Santa Maria Ground-Water Basin

Regarding the northern boundary, the earliest reports of hydrogeologic investigations conducted by the U.S. Geological Survey (Worts, 1951; Miller and Evenson, 1966) designated an approximate boundary along Black Lake Canyon within the Nipomo Mesa (see Figure 3-1). This designation was based on those investigators' interpretations of the extent of the fresh water-bearing deposits, as well as their understanding of ground-water flow directions, beneath the Santa Maria Valley, Orcutt Upland, and the Mesa. They described the aquifers within these deposits as likely being truncated at some point beneath the Mesa, thus creating a structural boundary to ground-water flow. The location of the aquifers' northern extent coincided with what was thought to be a hydrologic boundary (ground-water divide) where ground water flowed west to slightly southwestward, thus impeding flow north beyond this boundary.

Later reports by the California Department of Water Resources (DWR, 1970, 1975a) designated the northern basin boundary further south, at the southern escarpment of the Nipomo Mesa. This designation was based on DWR's interpretation of the aquifer extent and ground-water flow directions beneath the area. DWR suspected that the escarpment at the Mesa's southern edge had an "underground expression" limiting ground-water flow from the Santa Maria Valley to the Mesa; and DWR reported that ground-water flow at that boundary was to the west instead of continuing further north beneath the Mesa.

Subsequently, however, the previous boundary designations began to be questioned and were eventually modified. One U.S. Geological Survey report (Hughes, 1977) described the northern hydrologic boundary as being "poorly-defined," and DWR redefined the northern basin boundary location northward to designate a larger single ground-water basin that included the area from the Orcutt Upland to Arroyo Grande and Pismo Beach (see Figure 3-1). The latter modification was based on "recent geologic findings" indicating that there was no subsurface barrier to ground-water flow beneath the Mesa, including at its southern escarpment (DWR, 1980). Most recently, DWR maintained that the basin extended northward to encompass the Arroyo Grande/Pismo Beach area because, even though DWR determined that ground water within the Santa Maria Valley (at the Santa Maria River) flowed westward instead of toward the Mesa, there was no geological impediment to ground-water flow beneath the Mesa (DWR, 1999). This conclusion was based on the current understanding of the basin's geologic structure (aquifer extent and geometry, and fault locations, age, and characteristics).

Despite the reported lack of any prominent physical impediment to ground-water flow within the currently-reported larger single basin, the flow of ground water has historically been in a westerly direction beneath the Black Lake Canyon area within the Nipomo Mesa. The westerly flow in this area appears to result at the intersection of northwestward ground-water flow in the Santa Maria Valley and southwestward ground-water flow in the Arroyo Grande/Pismo Beach and northern Nipomo Mesa areas. These flows appear to "divert" each other westward beneath the Black Lake Canyon area such that north-south flow generally does not occur, either under historical or prevailing ground-water levels. Historical pumping depressions on the Nipomo Mesa have remained fairly localized and typically have not "crossed" the Black Lake Canyon area, which may be due to land use (and therefore pumping) limitations in and around the Canyon. For this reason, and because the District's focus on ground-water management is primarily in the Valley and immediately adjoining area, the portion of the ground-water basin north of the Canyon is not included in the modeled area.

Geology

A comprehensive study of the geology and hydrology of the Santa Maria Valley was completed by the U.S. Geological Survey (Worts, 1951) and several studies of note have subsequently been conducted on the hydrogeology and ground-water quality of the Valley (Hughes, 1977), the coastal portion of the basin (DWR, 1970), and the approximate northern half of the basin (DWR, 1958, 1999). These reports, as well as various other reports, maps, and Well Drillers' Reports, were evaluated as part of this study; the reports that were utilized are cited in the **References** section of this report and the wells with Well Drillers' Reports evaluated are located and identified on a map of the study area (Figure 3-2). A summary of the geology pertinent to development of the ground-water flow model follows.

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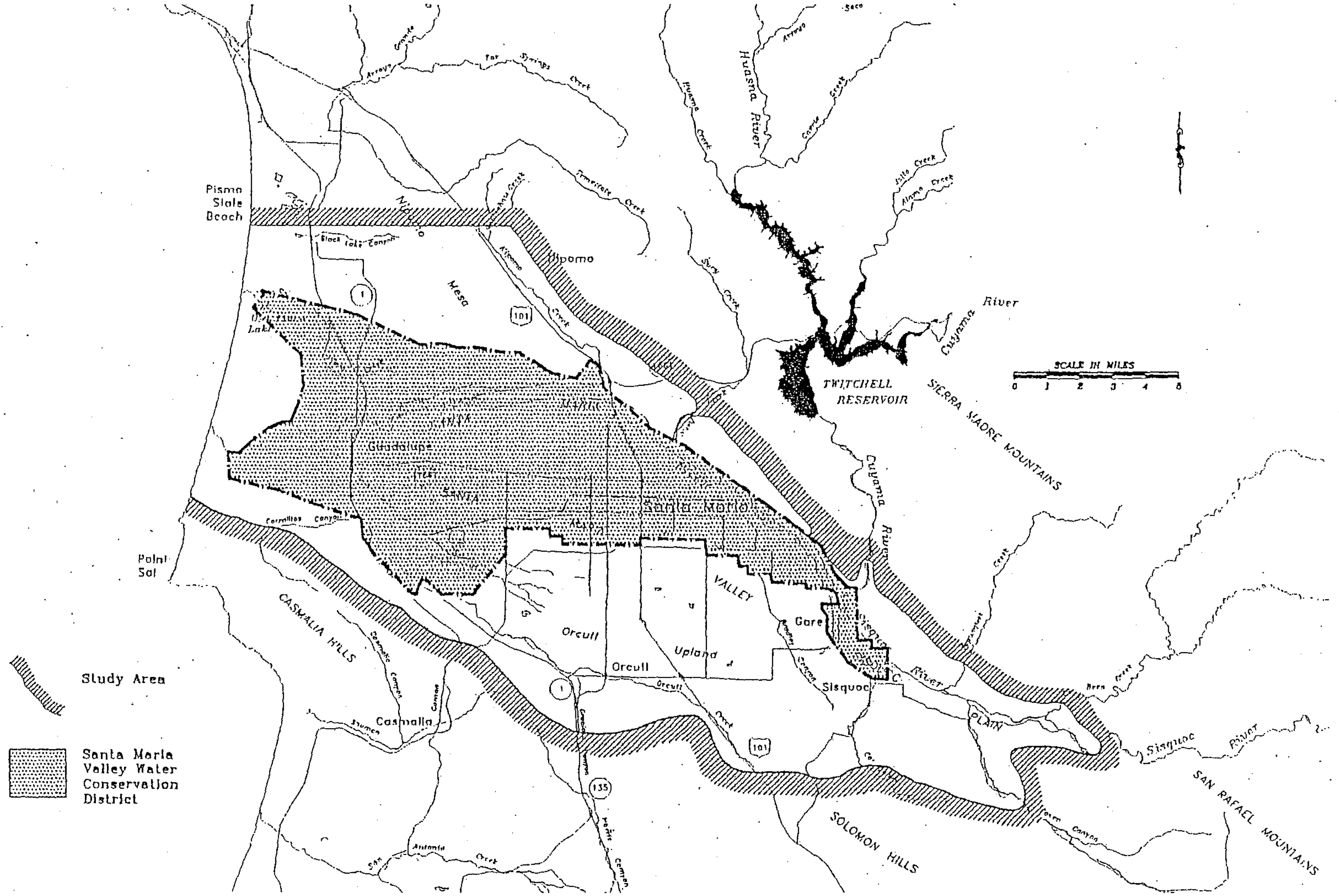

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Figure 2-1
Study Area and District Boundaries
Santa Maria Ground-Water Basin

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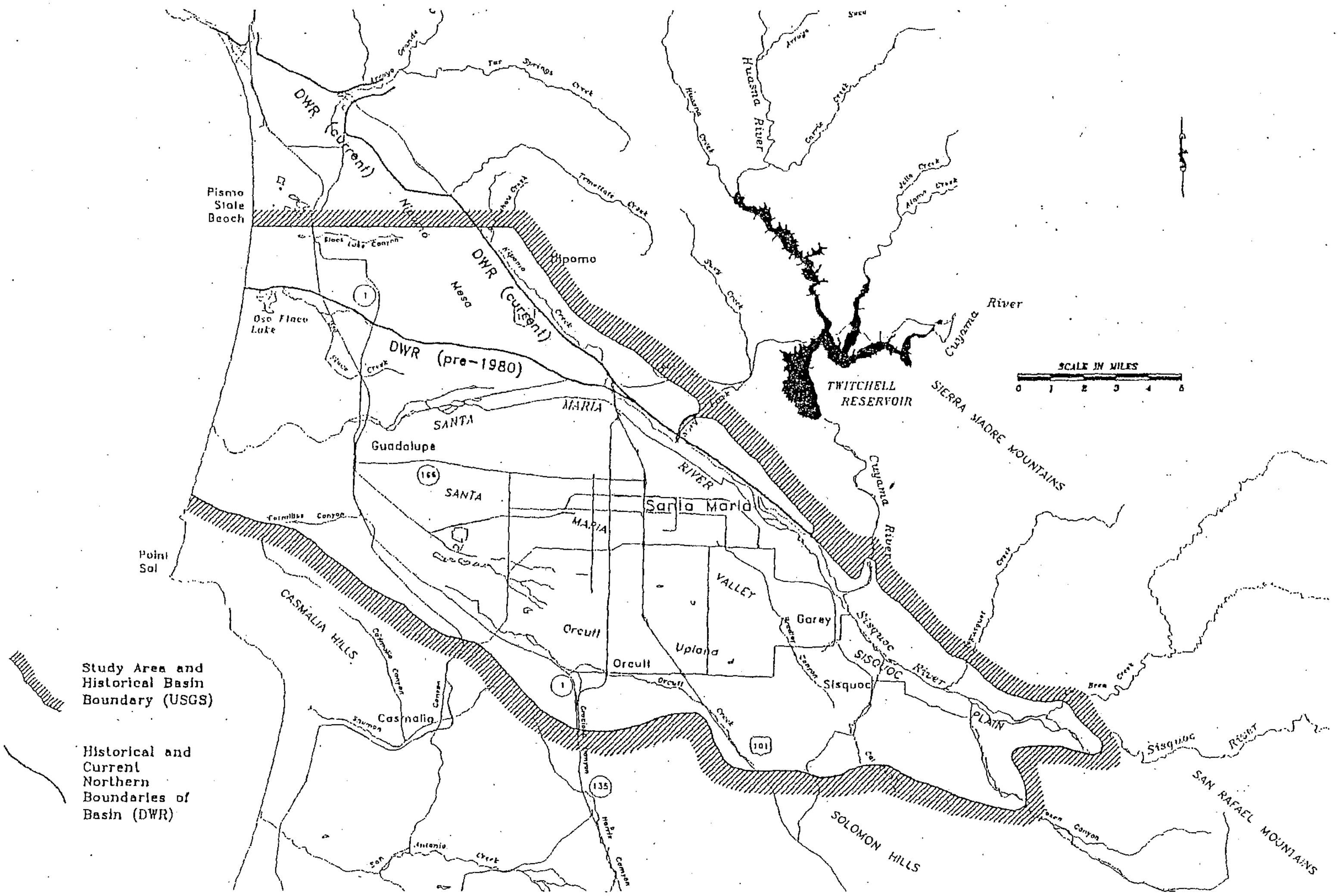

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Figure 3-1
Study Area and Historical Basin Boundary Designations
Santa Maria Ground-Water Basin

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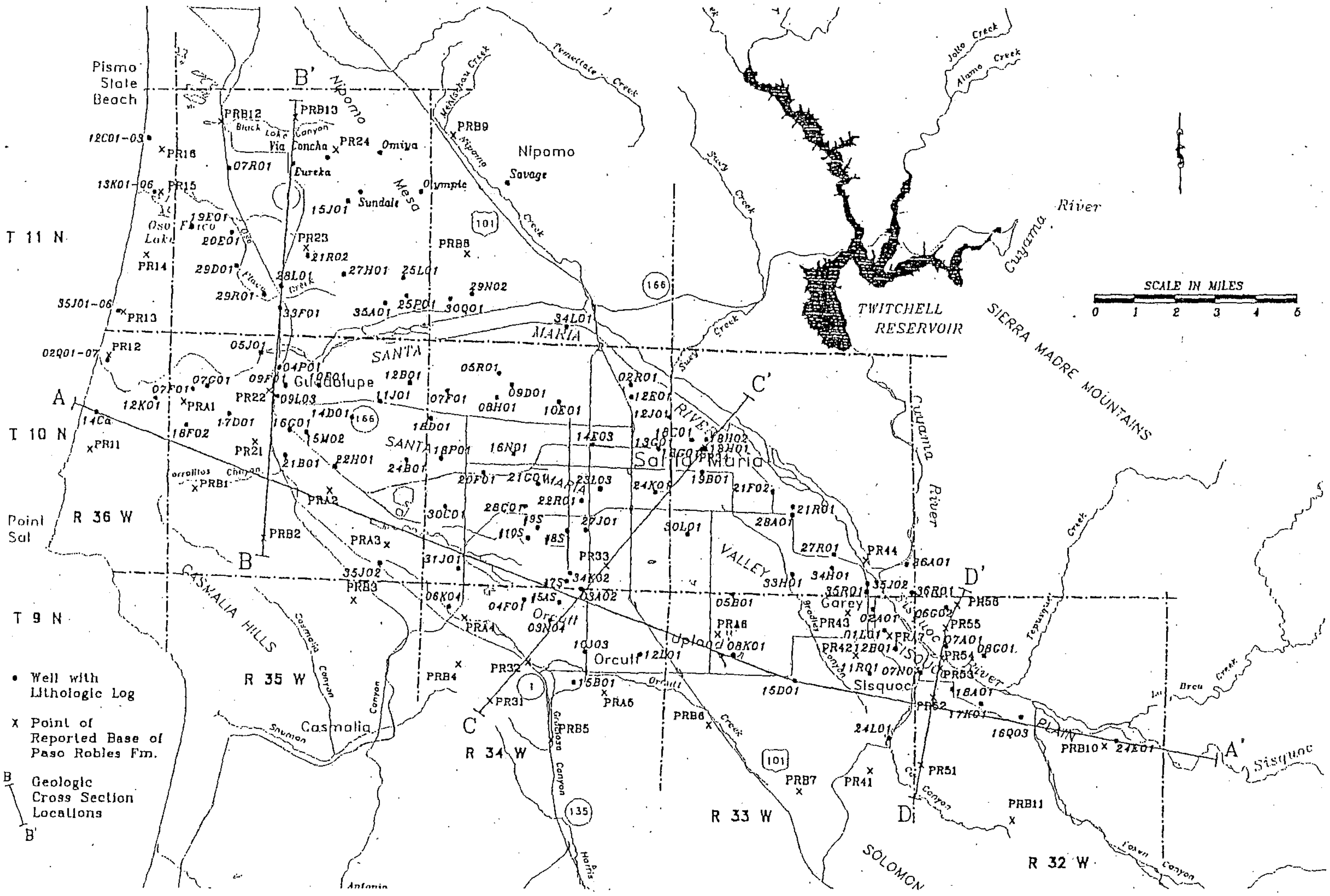

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Figure 3-2
Location of Geologic Cross Sections and Wells with Lithologic Logs
Santa Maria Valley Study Area

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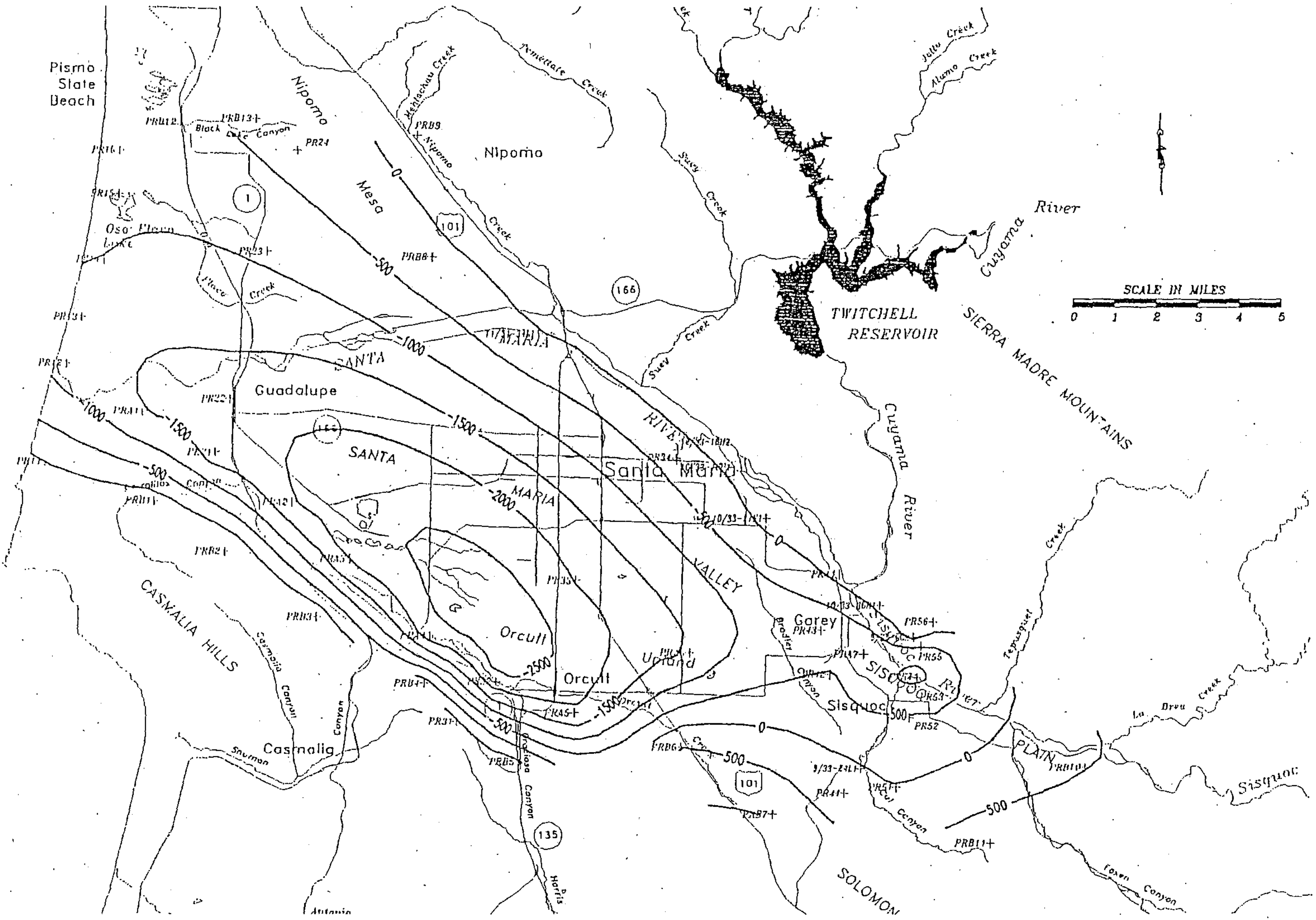

Contour Interval = 500 Ft

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Figure 3-3
Contours of Equal Elevation
Base of the Alluvial Deposits
Santa Maria Valley Study Area

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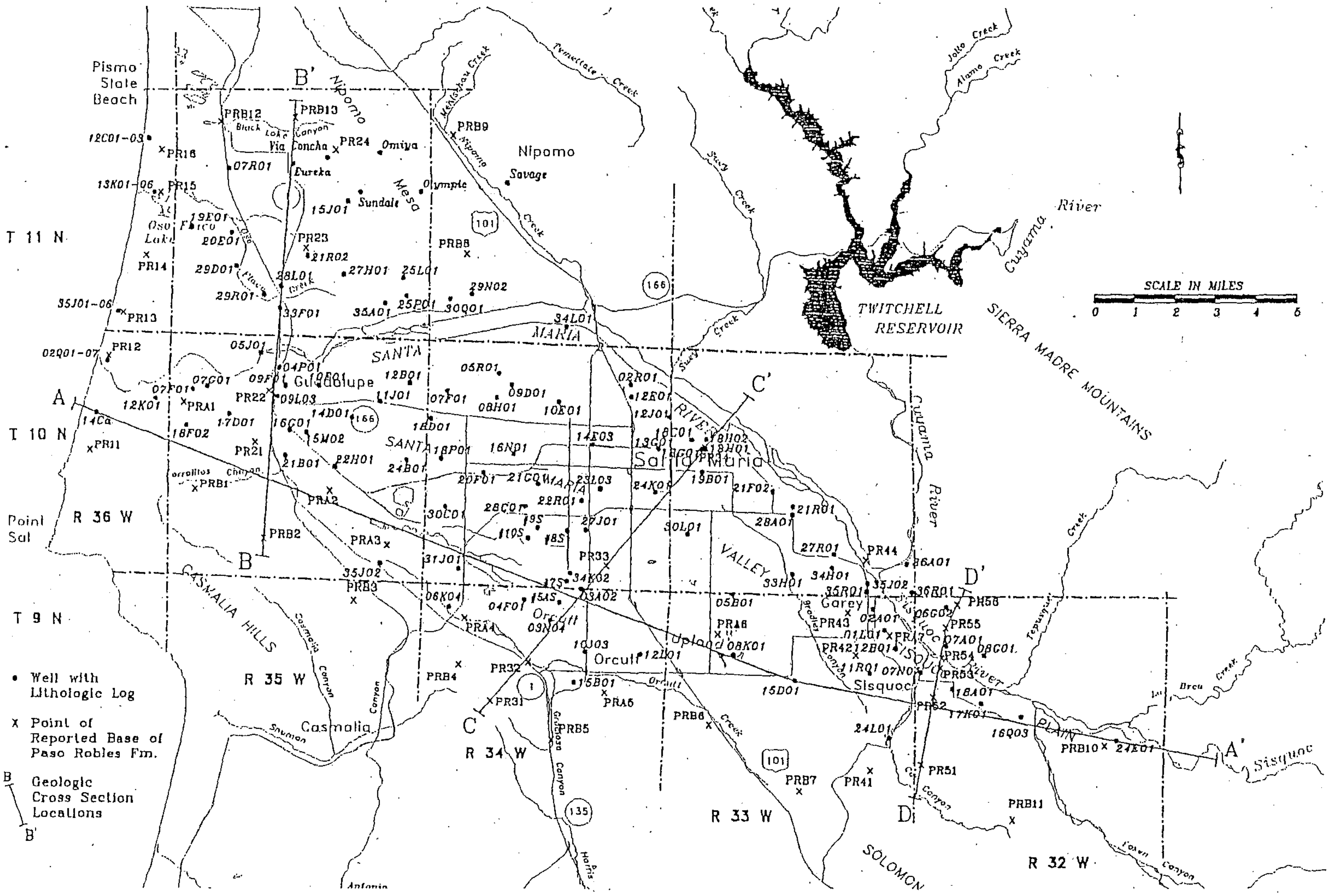

- Well with Lithologic Log
x Point of Reported Base of Paso Robles Fm.
B–B' Geologic Cross Section Locations

Figure 3-2
Location of Geologic Cross Sections and Wells with Lithologic Logs
Santa Maria Valley Study Area

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The Santa Maria ground-water basin is underlain by unconsolidated alluvial deposits of primarily gravel, sand, silt and clay that cumulatively range in thickness from 200 to 2,800 feet. These alluvial deposits comprise the basin's aquifer system. The alluvial deposits in turn overlie and fill in a natural trough ("syncline") composed primarily of older folded and consolidated sedimentary and metamorphic rocks ("bedrock"). A contour map of the base of the alluvial deposits (which is also the top of the consolidated rocks) was prepared that illustrates the trough shape of the basin within the study area, with the deepest portion beneath the Orcutt area (Figure 3-3). The consolidated rocks also flank the valley and comprise the surrounding hills and mountains; typically, the consolidated rocks do not yield significant amounts of ground water to wells. The geologic formations comprising the alluvial deposits and the geologic structure within the study area are illustrated in a generalized geologic map (Figure 3-4) and four geologic cross sections (Figures 3-5 through 3-8).

The alluvial deposits are composed of the Careaga Sand and Paso Robles Formation (Fm.) at depth, and the Orcutt Fm., Quaternary Alluvium, and river channel, dune sand, and terrace deposits at the surface (Worts, 1951). The Careaga Sand, which ranges in thickness from 650 feet to a feather edge, is identified as being the lowermost fresh water-bearing formation in the basin (DWR, 1970), resting on the above-mentioned consolidated rocks (specifically, the Tertiary-aged Foxen Mudstone, Sisquoc Fm., and Monterey Shale and the Jurassic/Cretaceous-aged Franciscan Fm., descriptions of which may be found in Worts, 1951). Overlying the Careaga Sand is the Paso Robles Fm., which comprises the greatest thickness of the alluvial deposits (from 2,000 feet to a feather edge); the thickest portion of this formation is located beneath the Orcutt area. Both the Careaga Sand and the Paso Robles Fm. underlie the great majority of the basin (see Figure 3-5). The Careaga Sand is mainly composed of white to yellowish-brown, loosely-consolidated, massive, fossiliferous, medium- to fine-grained sand with some silt and is reported to be predominantly of marine origin (Worts, 1951). The Paso Robles Fm. is highly variable in color and texture, generally composed of yellow, blue, brown, grey, or white lenticular beds of: boulders and coarse to fine gravel and clay; medium to fine sand and clay; gravel and sand; silt; and clay (Worts, 1951). This formation is reported to be primarily fluvial (stream-laid) in origin and there is no areal correlation possible between the individual beds, with the exception of a coarse basal gravel of minor thickness in the Santa Maria Valley oil field.

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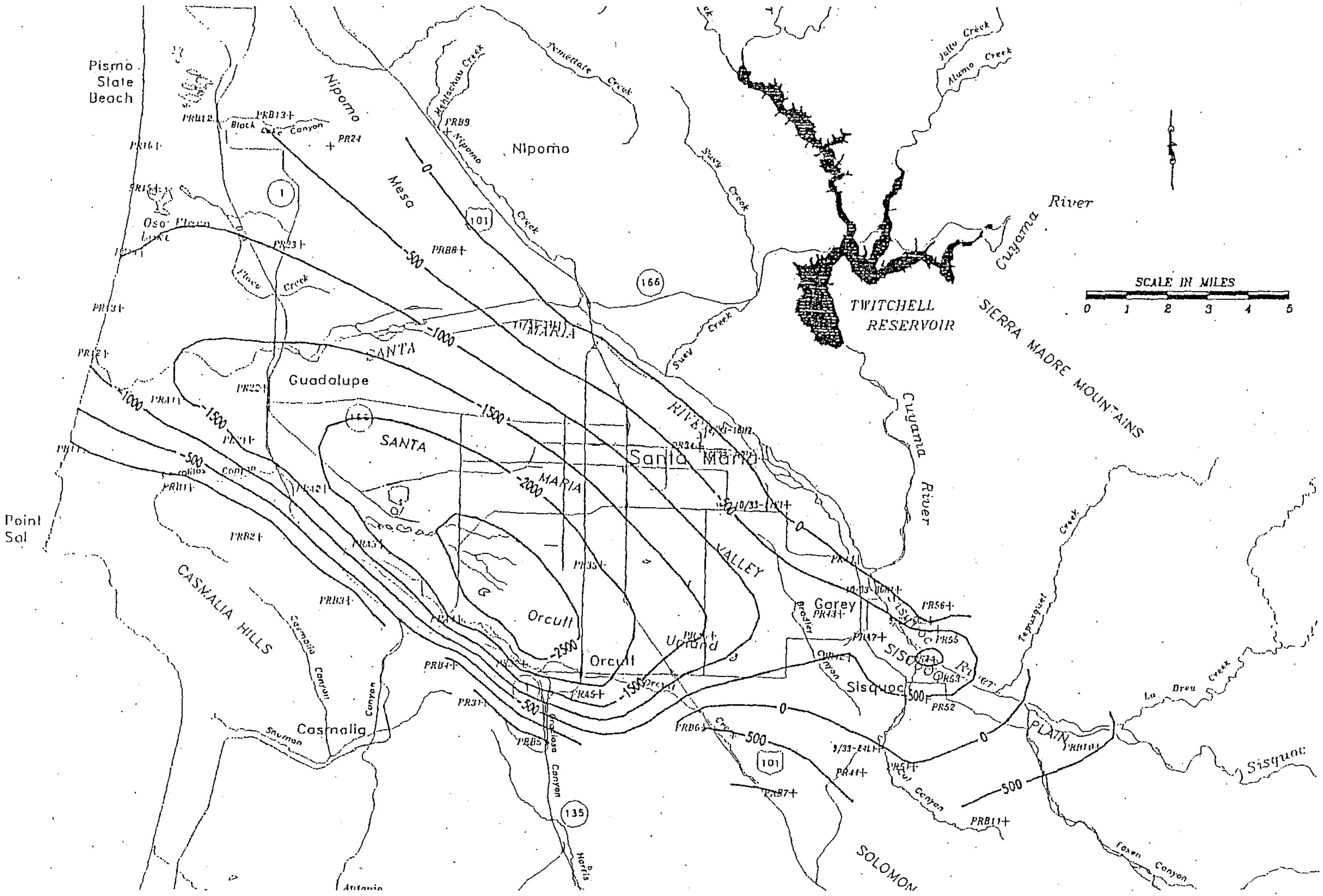

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Figure 3-3
Contours of Equal Elevation
Base of the Alluvial Deposits
Santa Maria Valley Study Area

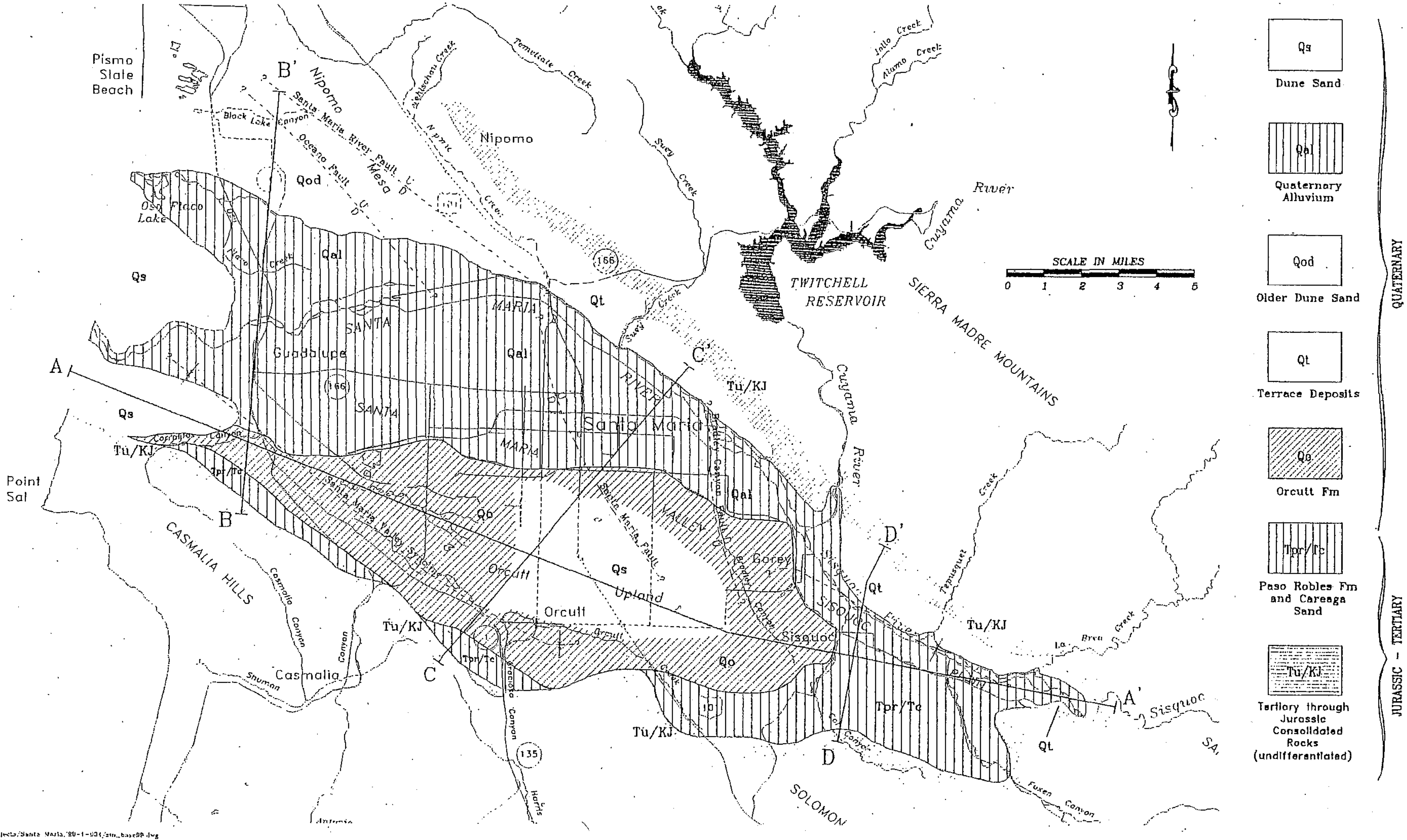

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Figure 3-4
Generalized Geologic Map
Santa Maria Valley Study Area

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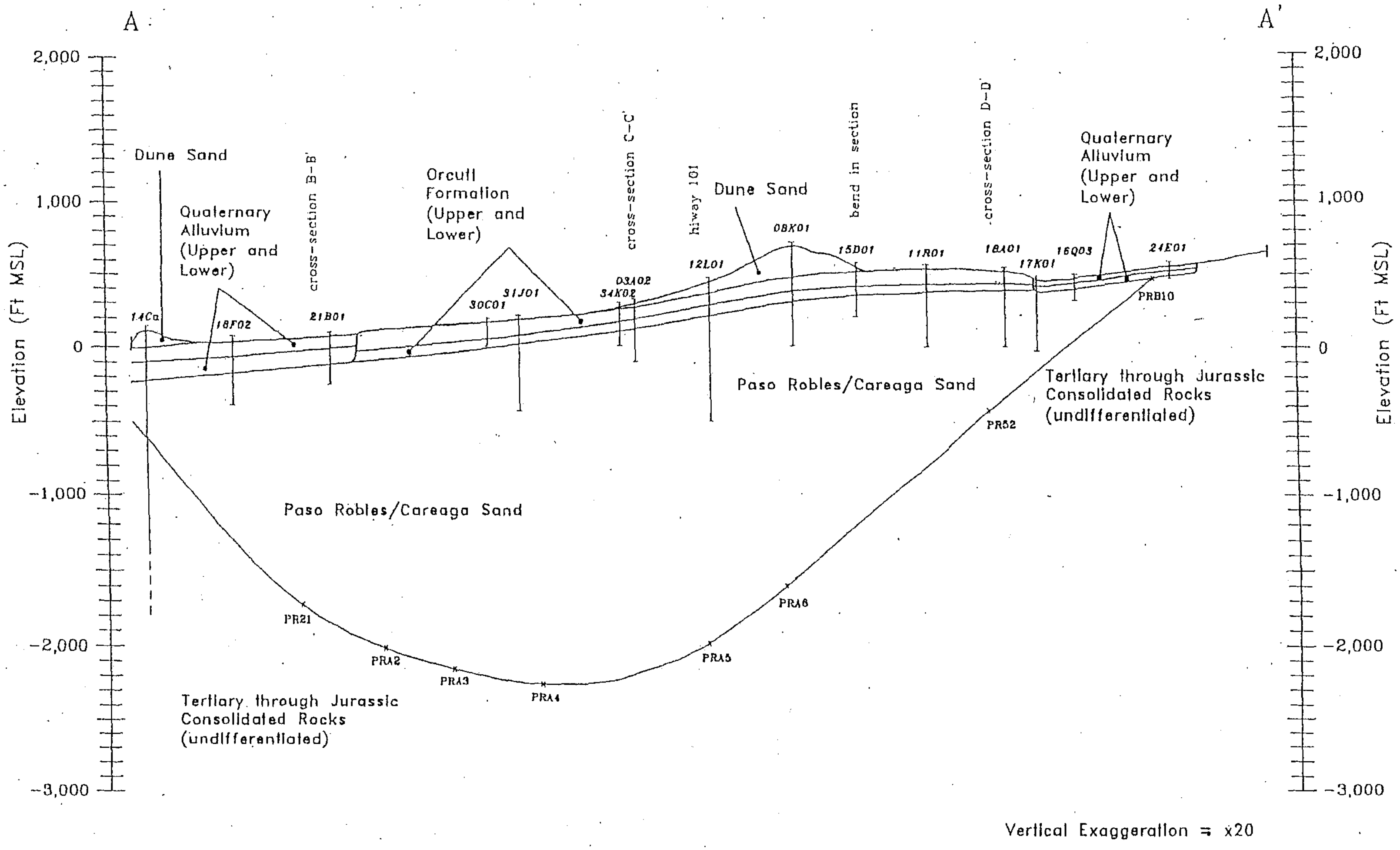

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Figure 3-5
Geologic Cross-Section A-A' (Large Scale)
Santa Maria Valley Study Area

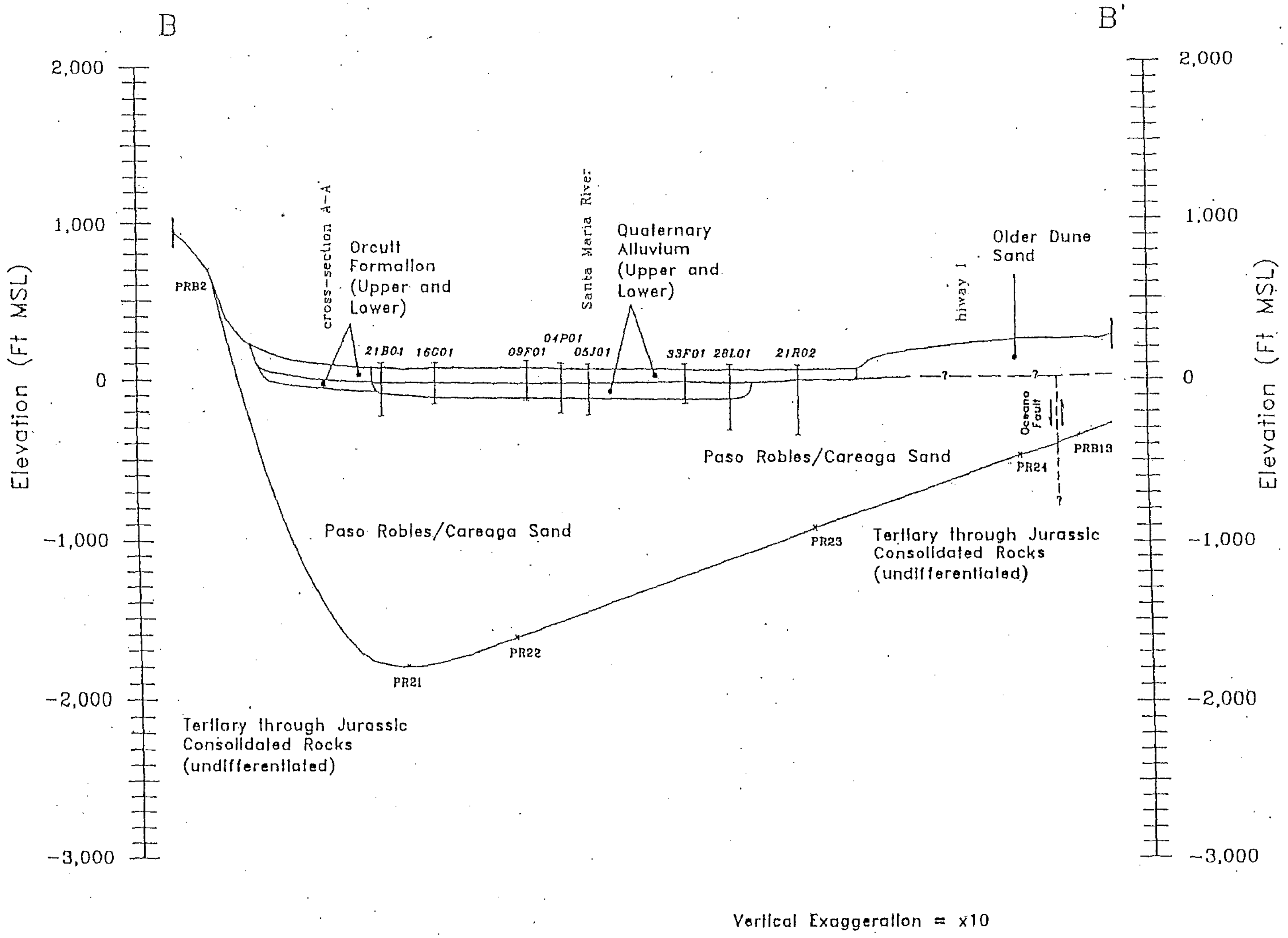

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Figure 3-6
Geologic Cross-Section B-B'
Santa Maria Valley Study Area

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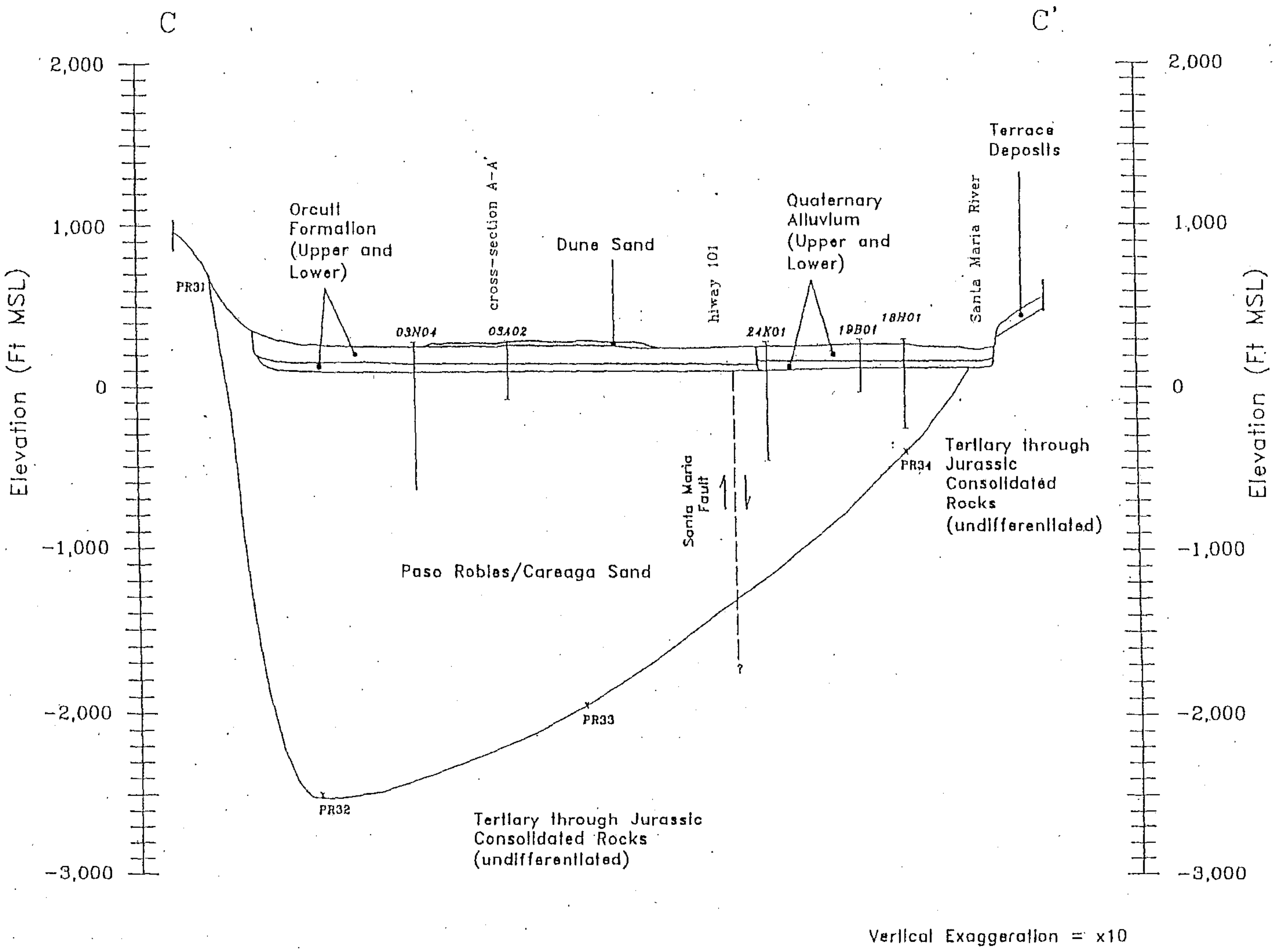

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Figure 3-7
Geologic Cross-Section C-C'
Santa Maria Valley Study Area

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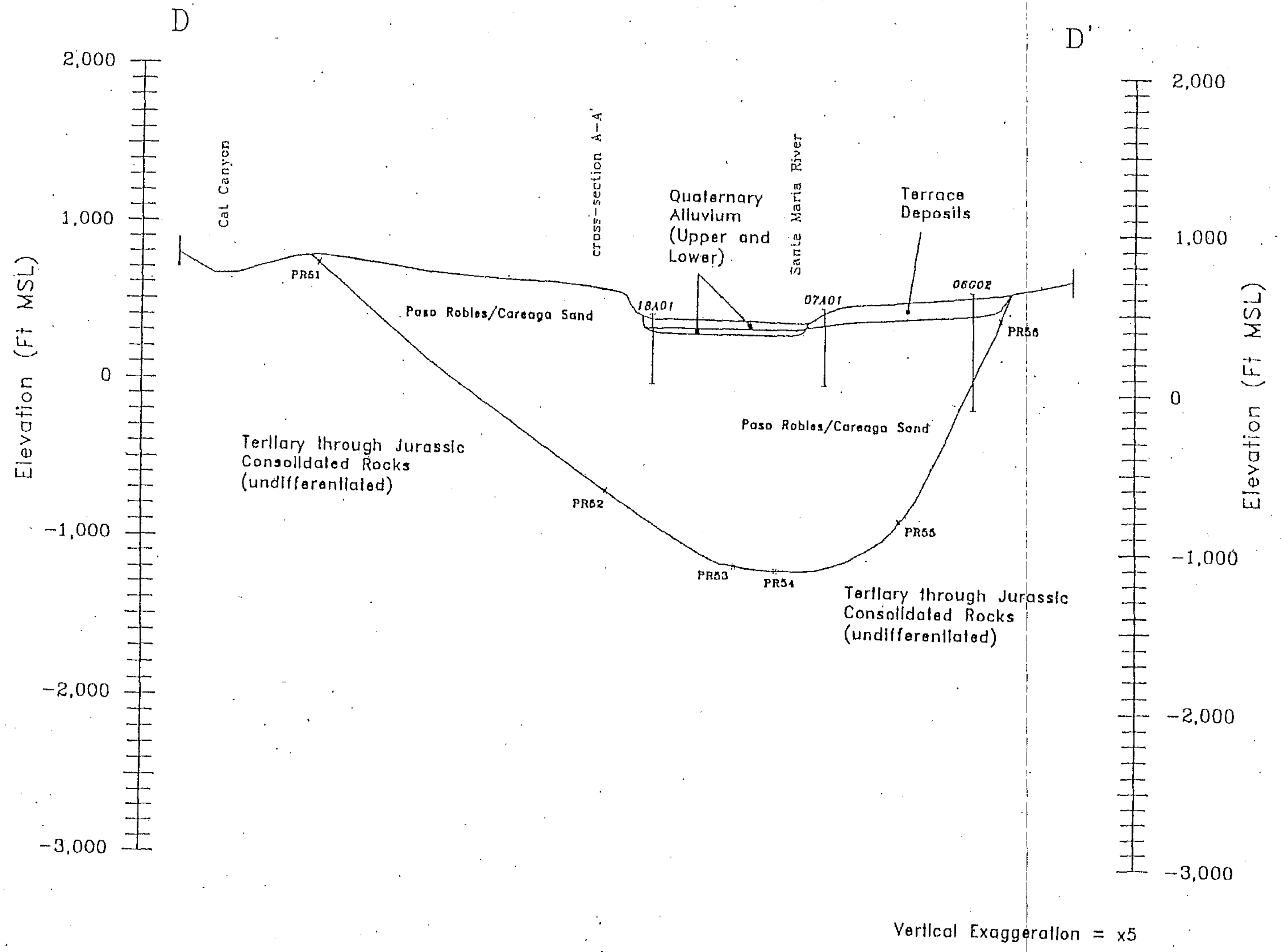

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Figure 3-8
Geologic Cross-Section D-D'
Santa Maria Valley Study Area

Above the Paso Robles Fm. and comprising the Orcutt Upland is the Orcutt Fm., which is typically 160 to 200 feet thick; in the remainder of the Valley area, the Paso Robles Fm. is overlain by the Quaternary Alluvium, which comprises the majority of the Valley floor and is typically 100 to 200 feet thick (see Figure 3-6). Further north in the Nipomo Mesa area, the Paso Robles Fm. is overlain by the Older Dune Sand, which comprises the Mesa and ranges in thickness from approximately 400 feet to a feather edge. Along the northeast edge of the Sisquoc plain, the Paso Robles Fm. is overlain by terrace deposits approximately 60 feet thick. The Orcutt Fm. is composed of conformable upper and lower units ("members"), both reported to be mainly of fluvial origin. The upper member generally consists of reddish-brown, loosely-compacted, massive, medium-grained clean sand with some lenses of clay, and the lower member is primarily grey to white, loosely-compacted, coarse-grained gravel and sand (Worts, 1951). Both members of the Orcutt Fm. become finer toward the coast. The Quaternary Alluvium is also composed of upper and lower members that are reported to be mainly fluvial in origin. The composition of the upper member becomes progressively finer toward the coast, with boulders, gravel, and sand in the Sisquoc plain area; sand with gravel in the eastern/central Valley area; sand with silt from the City of Santa Maria to a point approximately halfway to Guadalupe; and clay and silt with minor lenses of sand and gravel from that area westward. The lower member is primarily coarse-grained boulders, gravel and sand with minor lenses of clay near the coast. The Older Dune Sand is composed of loosely- to slightly-compacted, massive, coarse- to fine-grained, well-rounded, cross-bedded quartz sand that is locally stained dark reddish-brown (DWR, 1999). The terrace deposits, in general, are similar in composition to the coarse-grained parts of the Quaternary Alluvium.

The principal aquifers in the study area consist of the Paso Robles Fm., the Orcutt Fm., and the Quaternary Alluvium, although some wells have been reported to be completed in the Older Dune Sand of the Nipomo Mesa and the Dune Sand on the Orcutt Upland that pump minor amounts of perched water (Worts, 1951). It should be noted that the upper member of the Quaternary Alluvium is consistently finer-grained than the lower member throughout the Valley. Further, the upper member becomes finer grained toward the Ocean such that it confines ground water in the lower member from the approximate area of the City of Santa Maria's waste water treatment plant westward (approximately eight miles inland from the coast). The result of this has been artesian conditions in the western valley area (historically, flowing artesian wells were reported until the early 1940s in the westernmost portion of the valley) (Worts, 1951). In addition, many wells belonging to local farmers in the western valley area, specifically in the Oso Flaco area, began flowing again during winter 1999.

The geologic cross sections were located as such in order to illustrate several points about the study area geology pertinent to constructing the numerical model. Cross-section A-A' (see Figure 3-5) begins in the area near the mouth of the Santa Maria River, traverses the Orcutt Upland, and terminates in the Sisquoc plain area near Round Corral. It shows the relative thicknesses between the various geologic formations in the study area and the general "thinning" of the formations from the central valley area toward the Sisquoc Plain. This cross section also shows the Quaternary Alluvium and Orcutt Fm., essentially adjacent to each other and comprising the uppermost aquifer in the Valley, divided into the above-described upper and lower members.

Cross section B-B' (see Figure 3-6) begins in the Casmalia Hills, traverses the western portion of the Valley (near the City of Guadalupe) and the central Nipomo Mesa, and terminates in Black Lake Canyon. It shows the prominent asymmetrical syncline (folding of the consolidated rocks and Paso Robles Fm.) within the Valley, with the deepest portion of the basin toward the southern edge of the Valley, gradually becoming thinner and more shallow toward the north where it extends beneath the Nipomo Mesa. This cross section also shows that both the upper and lower members of the Quaternary Alluvium extend to the Santa Maria River, but only the upper member extends beyond the River to the southern edge of the Nipomo Mesa. Neither the upper nor lower member continues northward beneath any portion of the Mesa; instead, the Older Dune Sand comprises the Mesa's surface (Cleath & Associates, 1996; DWR, 1999).

Cross section C-C' (see Figure 3-7) begins in the Casmalia Hills, traverses the central/eastern portion of the Valley (near the City of Santa Maria), and terminates in the terrace adjacent to Suey Creek. It shows how the Orcutt Fm. (comprising the Orcutt Upland) sharply transitions into the Quaternary Alluvium (underlying the Valley area near the City), which terminates at the base of the cliffs above the Santa Maria River. This cross section also shows that the terrace deposits capping the cliffs above the River (near Suey Creek) are physically separated from the alluvial deposits of the basin and are therefore not hydraulically connected to the aquifer system of the basin.

Cross section D-D' (see Figure 3-8) begins in the Solomon Hills, traverses the central portion of the Sisquoc plain, and terminates above the terrace southeast of the confluence of the Cuyama and Sisquoc Rivers (along the northeastern edge of the Sisquoc plain). It shows that the Quaternary Alluvium within the Sisquoc Plain is of a much narrower width than in other parts of the study area and that the terrace deposits are physically (and therefore potentially hydraulically) connected to the basin's aquifer system.

It should be noted that several faults have been reported to be located in the Valley and through the Nipomo Mesa. The Santa Maria and Bradley Canyon faults, located in the Valley in the area between the City of Santa Maria and Fugler Point, are concealed and they are reported to be northwest-trending, high-angle faults, that vertically offset the consolidated rocks, Careaga Sand, and Paso Robles Fm., but not the overlying Quaternary Alluvium or Orcutt Fm. (Worts, 1951). The Oceano and Santa Maria River faults are of a similar nature (the latter fault also has a significant strike-slip component of movement), but they are located in the Nipomo Mesa and extend north toward Oceano. The maximum vertical offset on the Oceano fault is reported to be in the range of 300 to 400 feet within the Careaga Sand and Paso Robles Fm.; on the other faults, it is reported to be much less, within the range of 80 to 150 feet (Worts, 1951; DWR, 1999). However, these faults do not appear to affect ground-water flow within the study area, based on the review of historical ground-water level contour maps (Worts, 1951; LSCE, 1997; DWR, 1999). Lastly, there is no know structural (e.g., faulting) or lithologic isolation of the alluvial deposits from the Pacific Ocean (i.e., the Quaternary Alluvium, Orcutt Fm., Careaga Sand, and Paso Robles Fm. aquifers continue beneath the Ocean). Thus, at some unknown distance from the shore, the water in these aquifers changes from fresh to salt water, and the potential exists for the salt water to intrude into the coastal (landward) portions of the aquifers if hydrologic conditions within them were to change.

Hydrology

The aquifer system within the study area is comprised principally of the Paso Robles Fm., Quaternary Alluvium, and Orcutt Fm. (the Careaga Sand is included but typically not tapped by wells, due to its depth), and is essentially continuous throughout the study area, both areally and vertically. It extends from the head of the Sisquoc plain on the east to the Pacific Ocean on the west, from the Orcutt Upland on the south to the Nipomo Mesa on the north, and from the base of the Careaga Sand upward through the Paso Robles Fm. and into the Quaternary Alluvium and Orcutt Fm. The system also includes terrace deposits along the northeast edge of the Sisquoc plain and river channel deposits throughout the Valley that are hydraulically connected to the principal aquifers. The uppermost part of the aquifer system is comprised of the Quaternary Alluvium (in the Valley floor), Orcutt Fm. (in the Orcutt Upland), and the upper part of the Paso Robles Fm. (in the Nipomo Mesa), with the Paso Robles Fm and Careaga Sand comprising the lowest aquifer throughout the study area. The Orcutt Upland is elevated sufficiently that, in the southeastern portion of the Upland (from Orcutt to Garey and southward), the upper member of the Orcutt Fm. is typically not saturated; also, ground-water levels beneath the western portion of the Nipomo Mesa can rise sufficiently to saturate the Dune Sand and Older Dune Sand overlying the Paso Robles Fm.

The upper and lower members of the Quaternary Alluvium are the shallowest aquifers in the central to eastern part of the Valley, and they are essentially unconfined in these areas because they are composed primarily of sand and gravel with only discontinuous lenses of clay (no effective confining layers). In the western part of the Valley, the upper member acts as a confining layer to the lower member and the latter becomes a confined aquifer. The saturated portions of the upper and lower members of the Orcutt Fm. behave as unconfined aquifers because they also are primarily sand and gravel deposits with only discontinuous lenses of clay. The Paso Robles Fm. and Careaga Sand essentially act as one large continuous aquifer that is typically unconfined in the central to eastern part of the Valley (with localized areas of confinement beneath clay lenses) and confined in the western part of the Valley. Only a slight upward vertical gradient (a few feet of head difference) has historically been observed between the Paso Robles Fm. and uppermost aquifers (Worts, 1951). No confining layers are continuous across the study area between the aquifers (with the aforementioned exception of the Quaternary Alluvium in the western valley).

Ground-Water Levels

Ground-water levels within the study area have fluctuated greatly since the 1920's, when historical water level measurements began, with seasonal and long-term trends described herein. Hydrographs of ground-water elevations in the study area illustrate that a substantial decline in ground-water levels, from historical high to historical low levels, occurred between 1945 and the late 1960's with a progressively greater decline further inland from the coast (Figure 3-9). The decline ranged from approximately 20 to 40 feet near the coast, 70 feet near Orcutt, to as much as 100 feet further inland (in the area just east of downtown Santa Maria). This decline was apparently due to an increasing agricultural demand on the ground-water basin and slightly drier than normal climatic conditions during this period, as discussed in the subsections below.

Since then, a general long-term stability has been present as ground-water levels fluctuated between the historical low and near historical-high levels over alternating five- to 15-year periods. Whether near the coast or inland, ground-water levels showed this trend but with different ranges of ground-water level fluctuations (see Figure 3-9). Ground-water levels in the Valley have repeatedly recovered to near historical-high levels, including as recently as 1995; ground-water level data for wells in the Nipomo Mesa are shorter-term, but show a similar (although more subtle) trend of decline and recovery in the western Mesa. In the eastern Mesa, ground-water levels have remained relatively constant or declined somewhat. Along the coastal portion of the study area, ground-water elevations have typically remained above sea level throughout the historical period. As discussed in the subsections below, the periodic ground-water level fluctuations since the late 1960's (with a long-term stability) have apparently been due to intermittent ~~wet and dry~~ climatic conditions, with natural recharge during wet periods complemented by supplemental recharge along the Santa Maria River from the Twitchell Reservoir project (upon becoming fully operational in the late 1960's). In

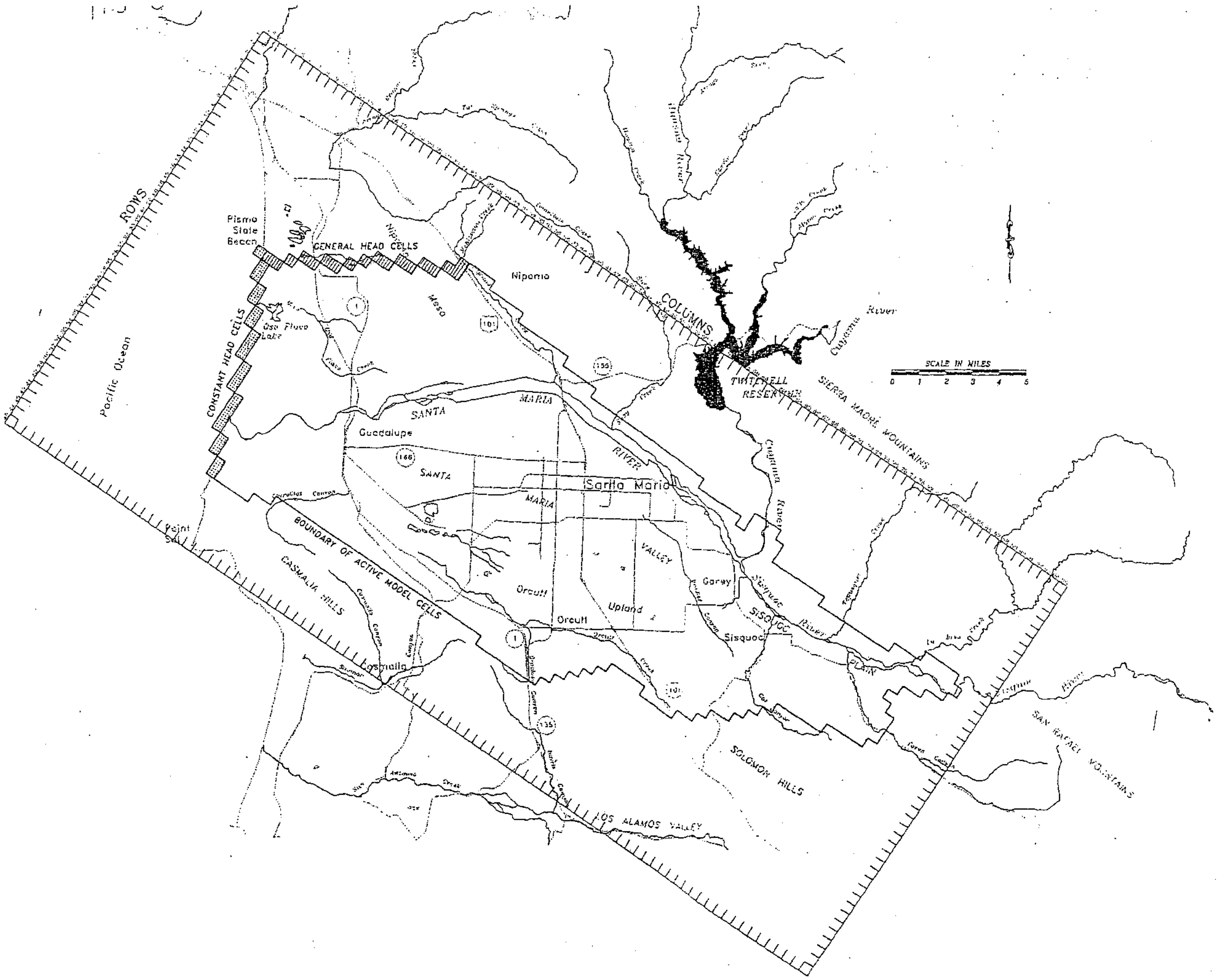

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Figure 4-2
Model Grid and Boundary Conditions
Santa Maria Ground-Water Basin

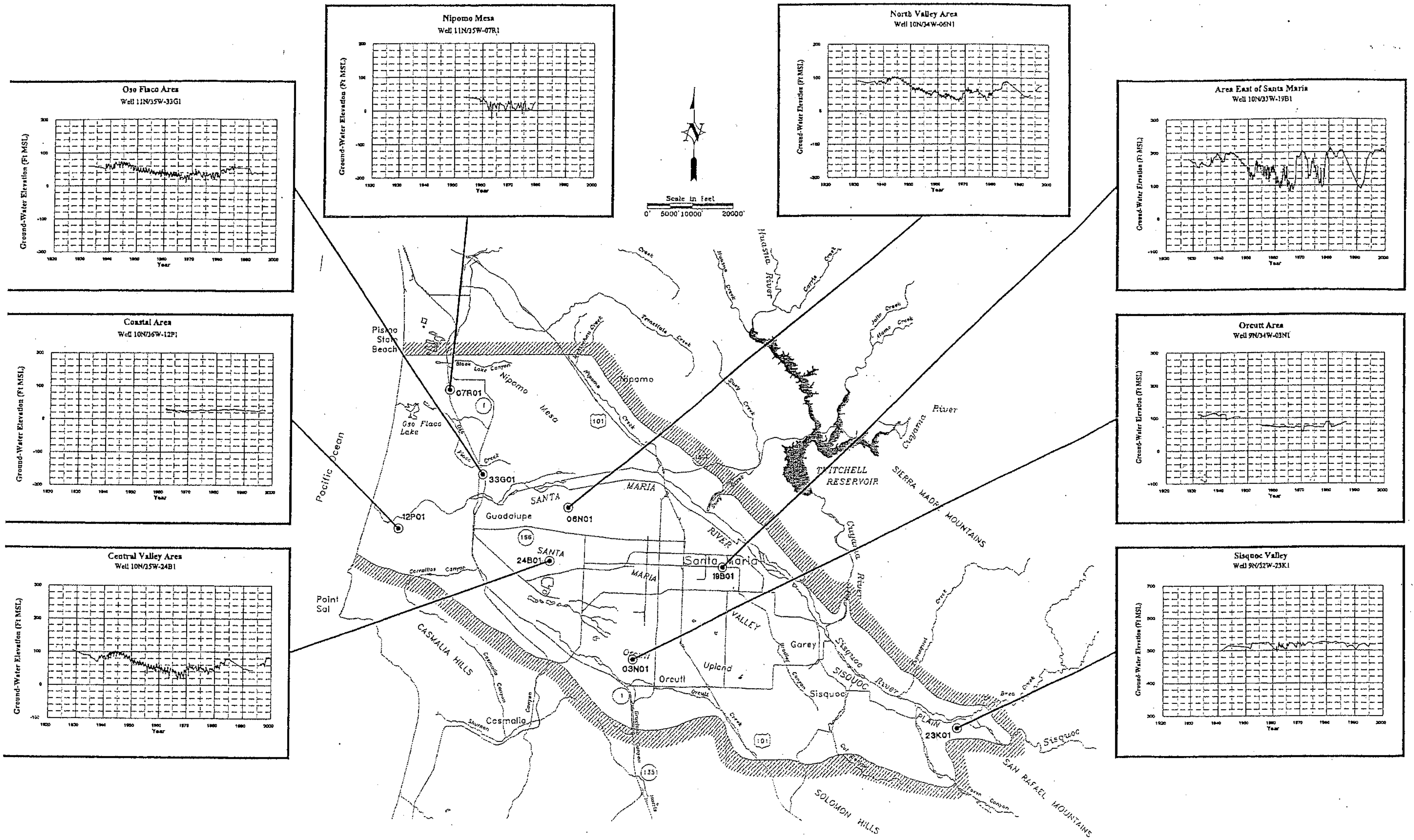

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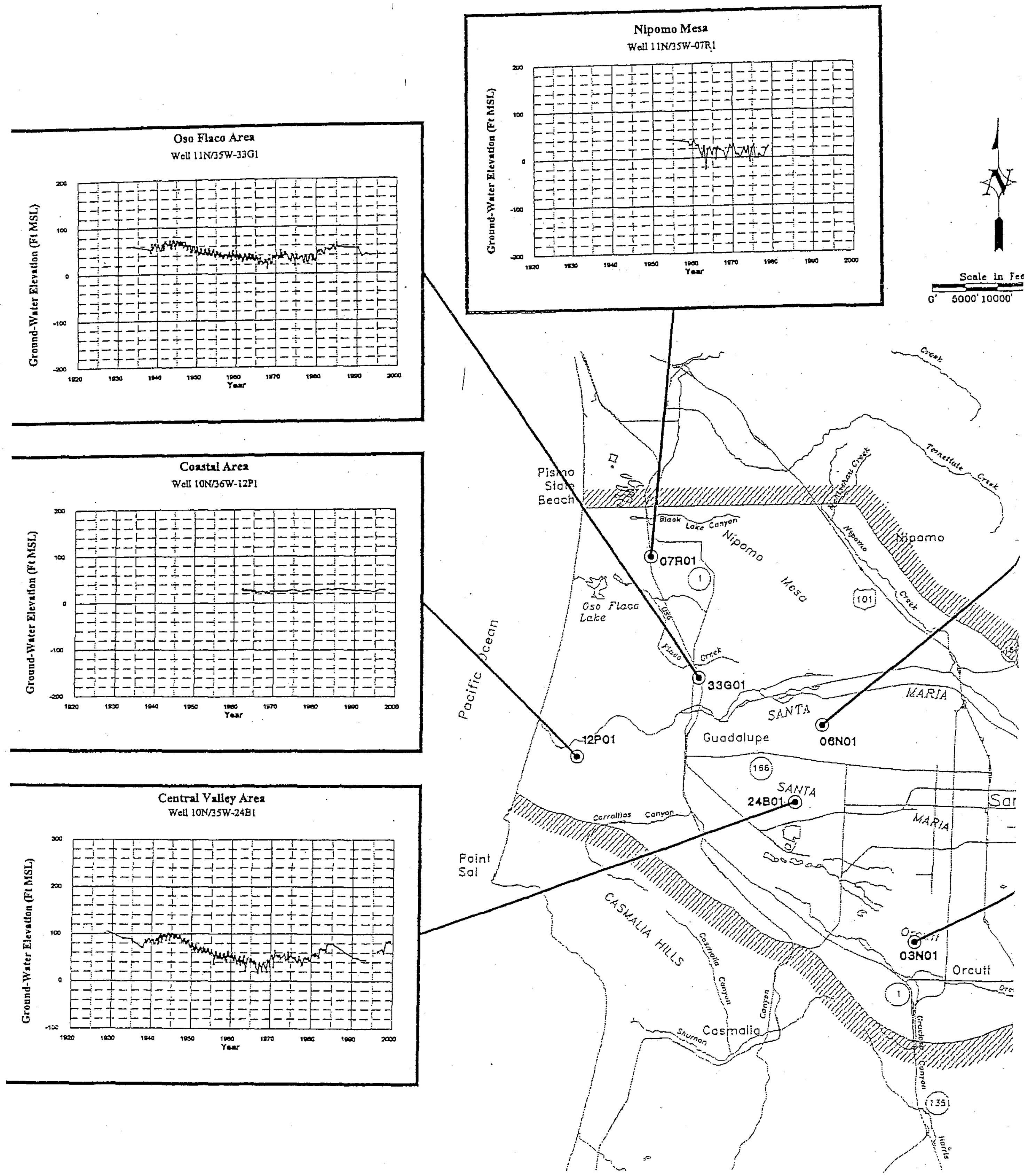
Figure 3-9
Historical Ground-Water Level Fluctuations
Santa Maria Valley Study Area



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addition, the long-term stability may have been partially due to a "leveling-off" of the agricultural demand on the basin.

Ground water beneath the valley has historically flowed to the west-northwest from the Sisquoc area toward the Ocean, including along the southern margin of the Nipomo Mesa, at times as far as the Oso Flaco Lake area. As noted above, ground-water levels have fluctuated between near historical-high and historical low levels since the early 1940's, and this is illustrated further in ground-water level contour maps for the following periods: 1944 (high), 1967 (low), and 1997 (high) (Figures 3-10, 3-11, and 3-12). Several points of interest in regard to the hydrologic conditions illustrated by the contour maps are that, first, a "flattening" of the water table beneath the central and western portions of the basins occurred between 1944 and 1967 as ground-water levels declined. The slope of the water table ("gradient") in these areas declined to less than one-half of the gradient observed during 1944, which has had the effect of slowing (but not stopping or reversing) the movement of ground-water through and out of the basin. This flattening has periodically fluctuated since 1967 as ground-water levels have alternately recovered and declined; some recovery is evident by 1997.

A second point is that the supplemental recharge from the Twitchell Reservoir project is visible in the ground-water level contour maps for 1967 and 1997 (Figures 3-11 and 3-12) where the contours are parallel to the Santa Maria River from Garey to the confluence with Suey Creek. This is also the case for several periods since 1967 when ground water was at near historical-high or historical low levels. As a result of the supplemental (Twitchell) recharge, even though ground-water levels beneath the eastern portion of the basin have fluctuated along with the rest of the basin during the historical period, the water table gradient has decreased only slightly between 1944 and 1997. The amount of the supplemental recharge to the basin, based on streamflow data from gauges located along the Sisquoc and Santa Maria Rivers, is discussed in a subsection below.

A third point is that, as noted above, coastal ground-water levels have typically remained above sea level and that the outflow of ground water from the basin has been maintained during conditions of both historical high and low ground-water levels. While the amount of outflow has varied with

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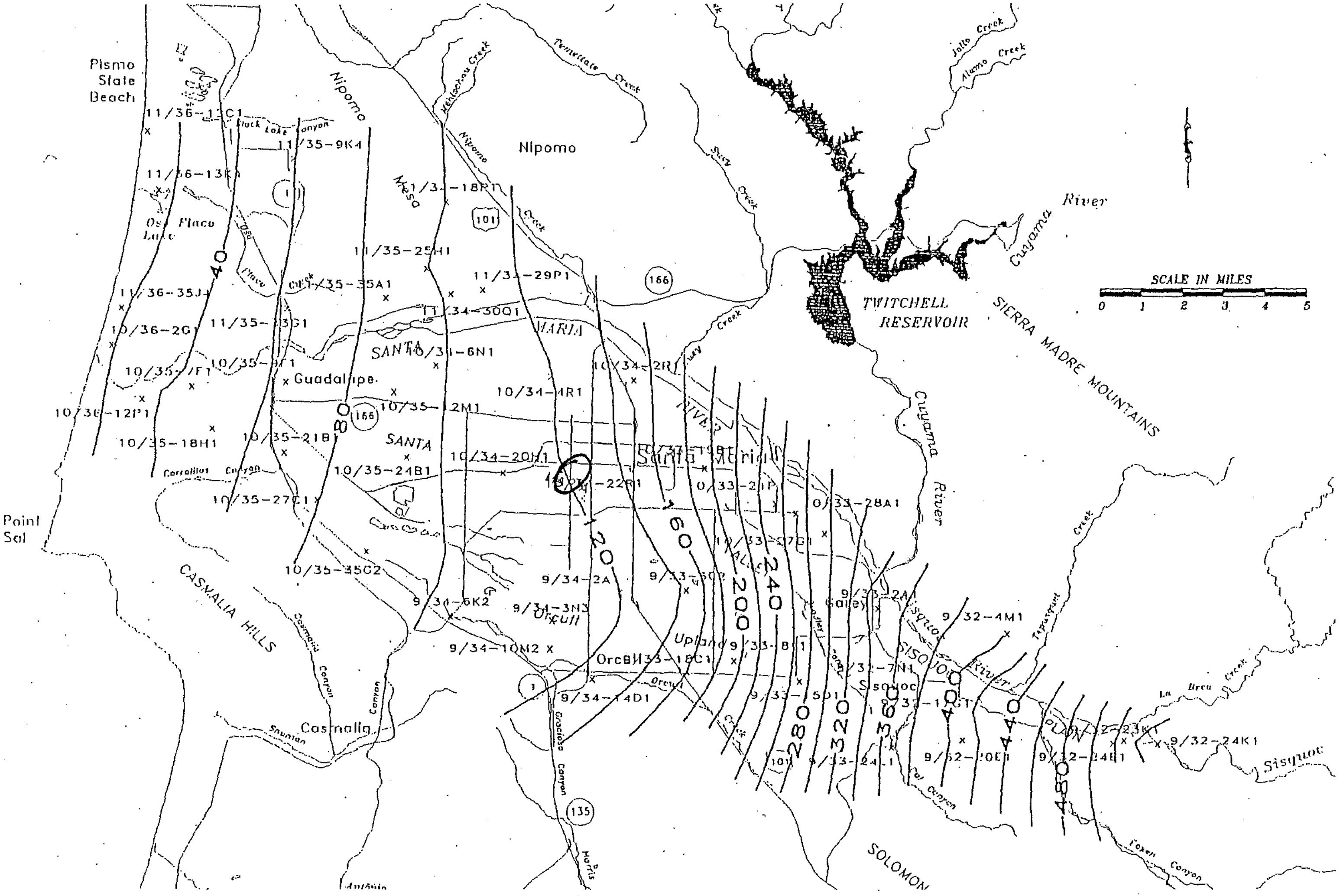

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Figure 3-10
Contours of Equal Ground-Water Elevation, Fall 1944
Santa Maria Valley Study Area

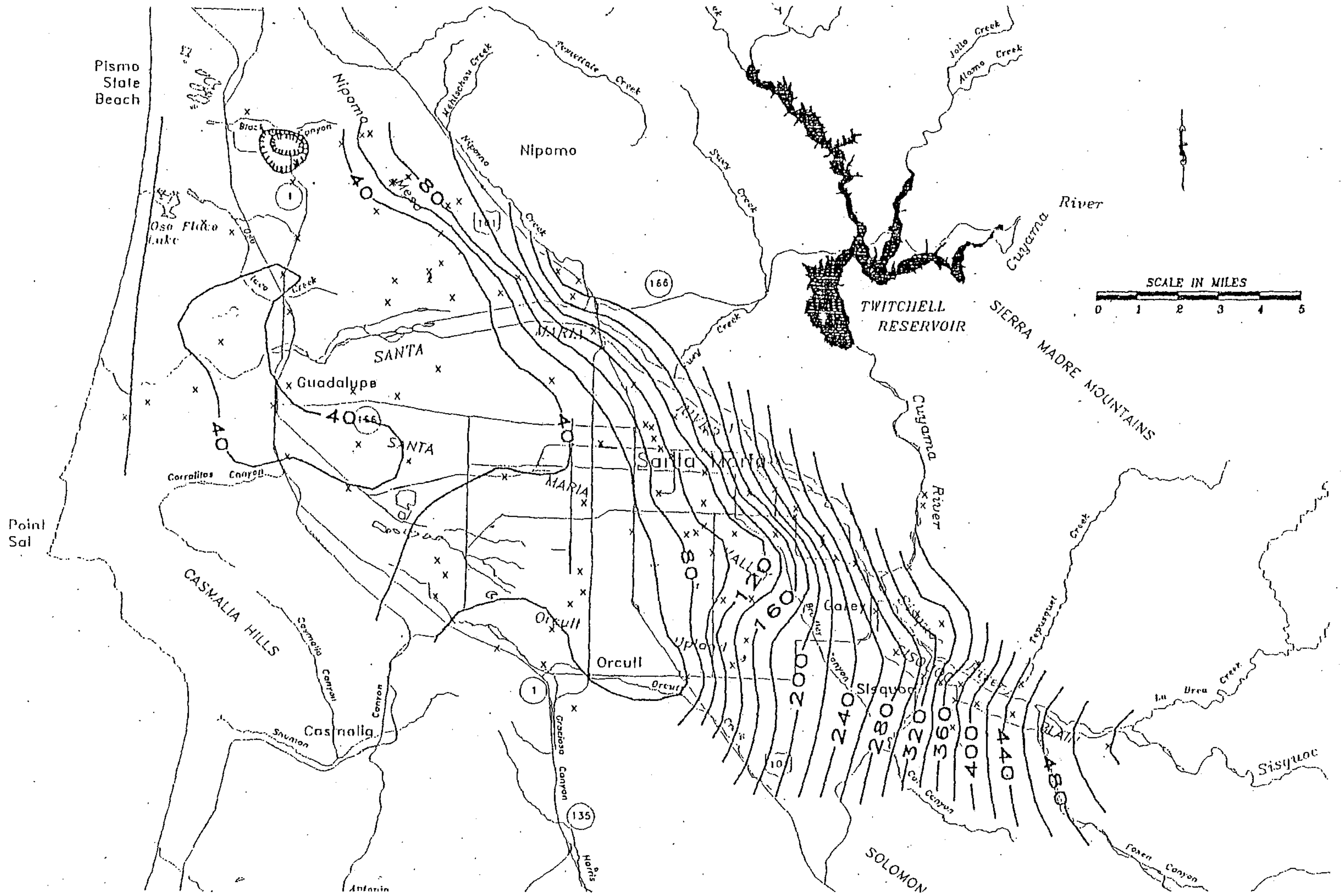

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Figure 3-11
Contours of Equal Ground-Water Elevation, Spring 1967
Santa Maria Valley Study Area

ground-water level fluctuations, the maintenance of positive water levels above sea level, which results in ground-water outflow, has likely precluded salt water intrusion of the basin. A localized area northeast of Oso Flaco Lake beneath the Nipomo Mesa experienced ground-water levels depressed below sea level during 1967 (see Figure 3-11); similar conditions have occurred during other periods since then when ground-water levels approached historical lows. This depression is near the northern edge of the study area and (when present) appears to reduce the amount of outflow from the aquifer(s) beneath the Nipomo Mesa to the ocean and induce ground-water flow from the Oso Flaco area northward toward the depression.

It should be noted that the review of historical ground-water conditions described above indicates that the basin has generally achieved a long-term stability in ground-water levels. Previous reports of the ground-water conditions in the basin had concluded that, at the current level of demand on the basin, it is in overdraft by approximately 20,000 acre-feet/year (Santa Barbara County Water Agency, 1994 and 1996). However, the hydrographs of historical ground-water levels throughout the basin (such as those in Figure 3-9) do not support the conclusion of perennial overdraft; rather, they indicate that the initial decline of ground-water levels between 1943 and 1967 was followed by a period of recovery, which has then been successively followed by alternating periods of decline and recovery between historical low and near historical-high ground-water levels through 1997. The nature of these historical ground-water level fluctuations does not support the existence of an "average annual" or continuous overdraft; instead, they indicate that basin ground-water storage has repeatedly fluctuated between several years of decline followed by several years of gain. Ultimately, the numerical ground-water flow model described herein was utilized to analyze ground-water level and storage changes over selected study periods to assess both the perennial yield of the basin and the status of the basin relative to that perennial yield; i.e., whether it is in overdraft. That assessment is described in detail in Chapter V below.

Aquifer Characteristics

Information about the aquifer characteristics throughout the study area was available from published reports, selected consultants' reports, and numerous Well Drillers' Reports. The information consisted of hydraulic conductivity values from aquifer tests conducted in a few wells (Worts, 1951) and specific capacity values from pumped well tests conducted in several wells (Hughes and Freckleton, 1976, and from Well Drillers' Reports). The specific capacity values were evaluated in relation to the individual well construction and lithology details to estimate aquifer transmissivity and hydraulic conductivity values. The locations of the wells and the hydraulic conductivity values for the particular aquifers are identified on a map of the study area (Figure 3-13). Information about aquifer storage coefficients was also available from selected reports, although this information was much less extensive than for specific capacity and hydraulic conductivity values.

The Quaternary Alluvium comprises the most permeable aquifer in the study area, with hydraulic conductivity values of about 4,500 gpd/ft^2 in the Sisquoc plain gradually declining westward to about 2,000 gpd/ft^2 near Guadalupe. In the eastern part of the study area, the upper and lower members of the Quaternary Alluvium serve as aquifers and their respective hydraulic conductivity values are described as being quite similar, as are their lithologies (Worts, 1951). Thus, the 4,500 gpd/ft^2 value represents both members in this area. The hydraulic conductivity values of both members decrease toward the central part of the study area and presumably to a greater degree in the upper member, which becomes finer than the lower member here (as described in the previous subsection). The 3,500 to 3,700 gpd/ft^2 values are representative of the lower member in this area; values for the upper member are thought to be somewhat lower than that (Worts, 1951) although aquifer/pump test information specific to the upper member was not available in this area (the wells are not completed solely in the upper member, apparently because only a small portion of it is saturated here). In the western part of the study area, the hydraulic conductivity values decrease further, reflecting the continued "fining" of the Quaternary Alluvium toward the coast. The lower member has an approximate hydraulic conductivity value of 2,000 gpd/ft^2, and the upper member is assumed to have

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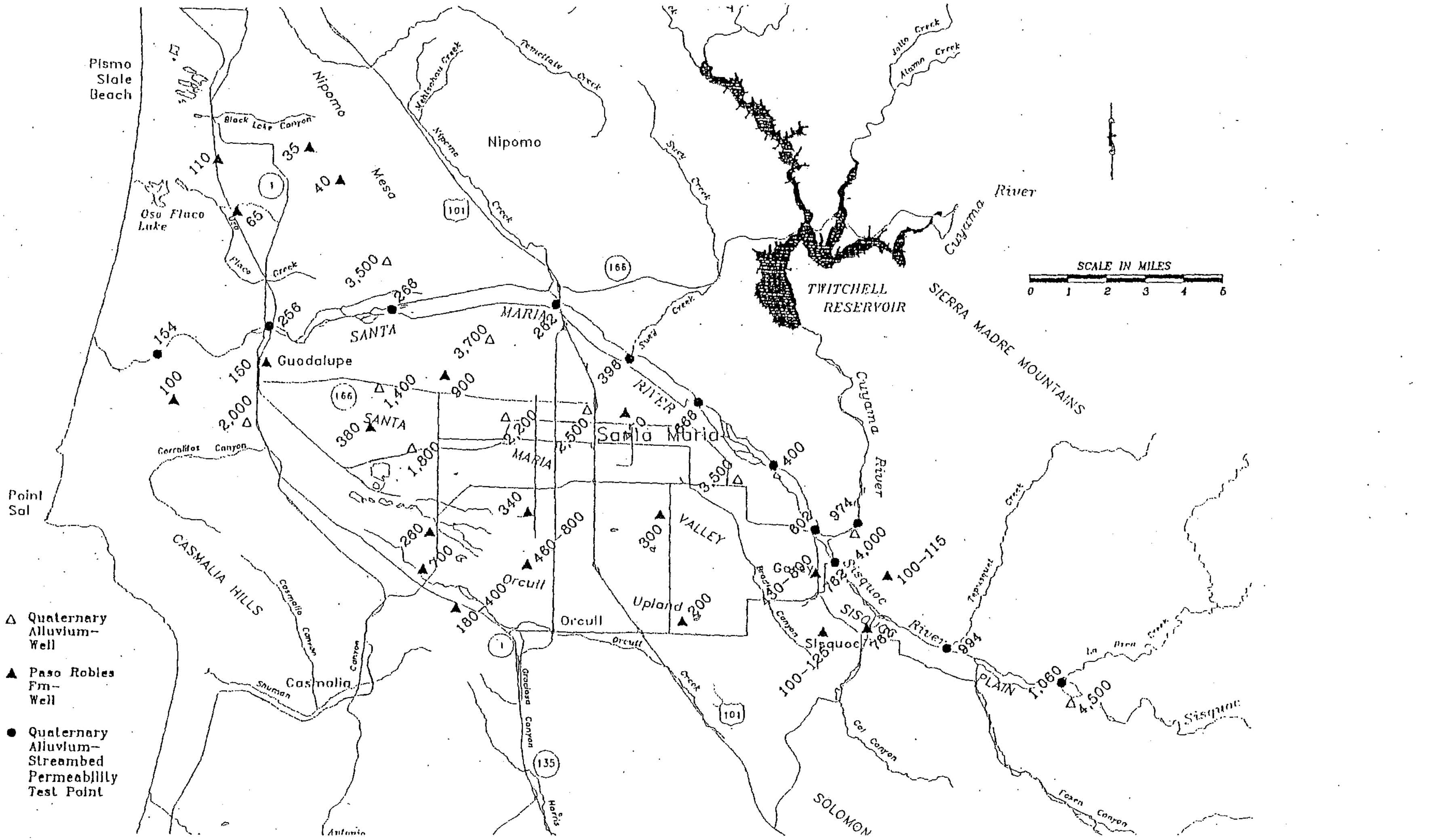

Values in gpd/ft^2 (streambed point values are vertical permeabilities)

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Figure 3-13
Distribution of Aquifer Hydraulic Conductivity Values
Quaternary Alluvium and Paso Robles Fm
Santa Maria Valley Study Area

a much smaller value because it serves as a confining layer (to the lower member) instead of as an aquifer (essentially no wells are completed solely in the upper member here).

The Paso Robles comprises by far the largest aquifer in the study area, with hydraulic conductivity values ranging between about 100 and 400 gpd/ft^2 in the Sisquoc plain, Orcutt Upland, and central part of the Valley, with slightly lower values ranging between about 15 and 110 gpd/ft^2 in the western part of the Valley and in the Nipomo Mesa. The estimated hydraulic conductivity values do not appear to vary greatly by depth within the formation, which is consistent with its lithology consisting of repeated lenticular (lense-shaped and not extensive) beds of variable cobbles, gravel, sand, silt, and clay throughout the thickness of the formation. Examination of the individual well construction and lithology details that were the basis for the estimates show that those wells are typically screened across several hundred feet of the Paso Robles Fm.; thus, the hydraulic conductivity values are "averages" for the formation.

The hydraulic conductivity of the Careaga Sand (Worts, 1951) was estimated from laboratory testing of samples of the formation (aquifer/pump test data were not available since essentially no wells in the basin are completed solely in the Careaga Sand); the average value was approximately 70 gpd/ft^2, which is assumed to apply to all portions of the Sand throughout the study area. Aquifer/pump test data were also not available for the Orcutt Fm., Older Dune Sand, or terrace deposits, again because so few wells are completed solely within these deposits. Their hydraulic conductivity values were estimated to be approximately two-thirds that of the adjacent portions of the Quaternary Alluvium, based on their respective lithologies, approximately 1,300 to 2,700 gpd/ft^2.

Vertical hydraulic conductivity values for the river channel deposits were determined from in-situ permeability tests at various points along the portions of the Santa Maria, Sisquoc, and Cuyama Rivers within the Valley (Worts, 1951). The values ranged between 1,060 gpd/ft^2 in the Sisquoc plain gradually declining westward to 154 gpd/ft^2 near the mouth of the Santa Maria River. This gradual westward decline in hydraulic conductivities is consistent with the gradual fining of the channel deposits between the Sierra Madre and San Rafael Mountains (the source area of the deposits) and the coast.

The specific yield (average values) of the study area aquifers have been reported to be as follows: Paso Robles Fm. and Careaga Sand, 8 to 12 percent in the Valley and Nipomo Mesa; Quaternary Alluvium, approximately 13 percent in the Valley; and Older Dune Sand, approximately 13 percent in the Nipomo Mesa (DWR, 1999). Storativity values for the portions of the aquifers that are under confined conditions were not available from reports, but were estimated to be 0.0001 based on typical values for similar aquifers.

Precipitation and Streamflow

A fairly comprehensive study of the surface water resources of the Santa Maria Valley was completed by the U.S. Geological Survey (Thomasson, 1951) describing the Valley's drainage system, the areal distribution of rainfall, and the relation between rainfall and runoff. That report was evaluated as part of the current study, which evaluates the surface water resources through 1997 in order to better understand historical trends in ground-water level fluctuations throughout the study area. Historical precipitation and streamflow records for the area were compiled to evaluate monthly, annual, and long-term characteristics of rainfall and of flows within the major rivers and creeks; the locations of the recording gauges and their respective periods of record are shown on a map of the study area (Figure 3-14). A summary of the rainfall and streamflow characteristics pertinent to development of the ground-water flow model follows.

Three precipitation gauges are located throughout the study area: Guadalupe, Santa Maria (currently at the Airport and previously downtown), and Garey. The average amount of rainfall measured at the Santa Maria gauge (the most centrally located gauge in the study area) is 13.4 inches/water year, as shown in a hydrograph of the historical annual precipitation (Figure 3-15); a review of the monthly records indicates that the majority of rainfall occurs during the months of November through April. The long-term rainfall characteristics are shown in a cumulative departure curve of the historical

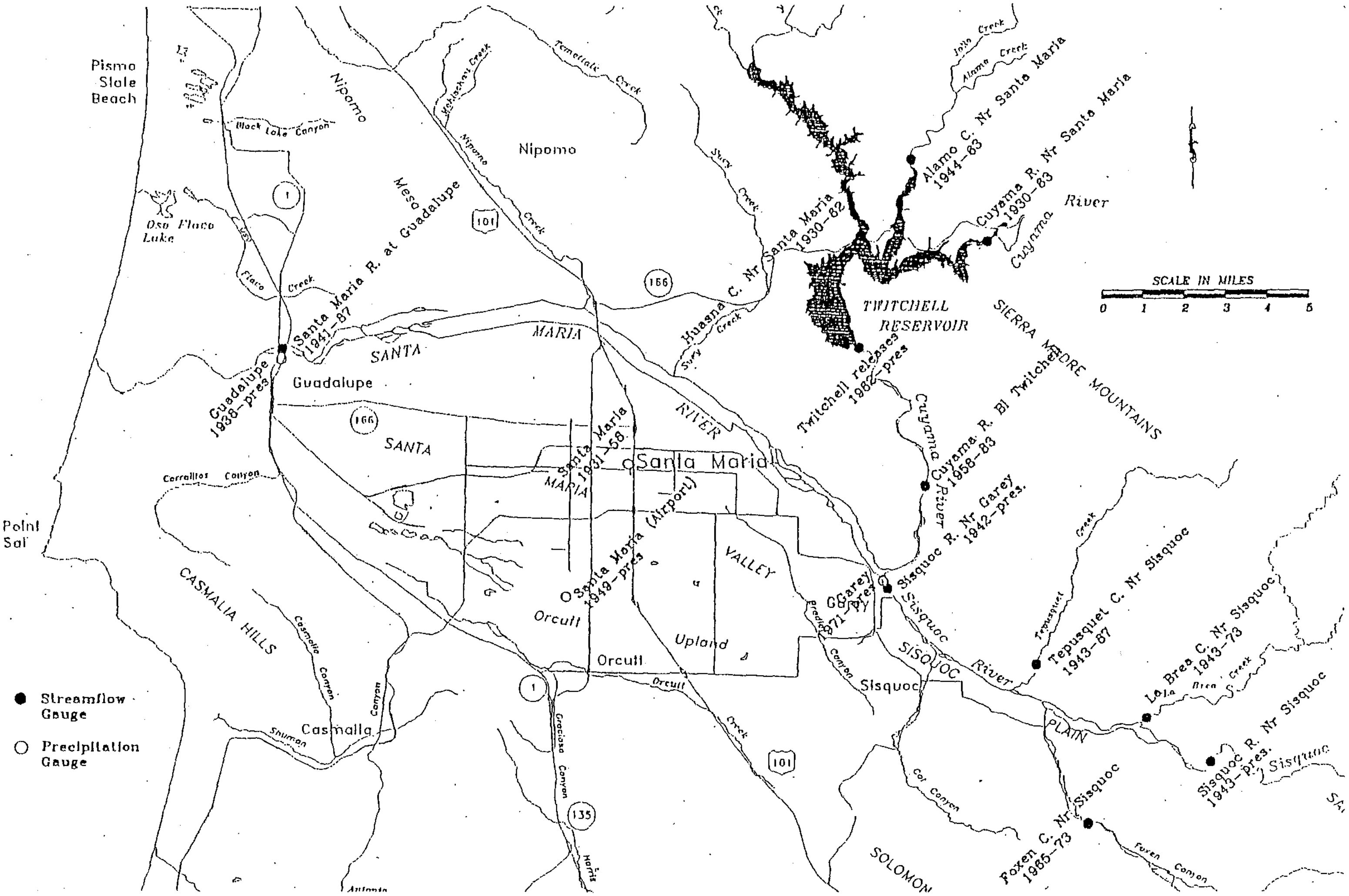

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Figure 3-14
Streamflow and Precipitation Gauge Locations
Santa Maria Valley Study Area

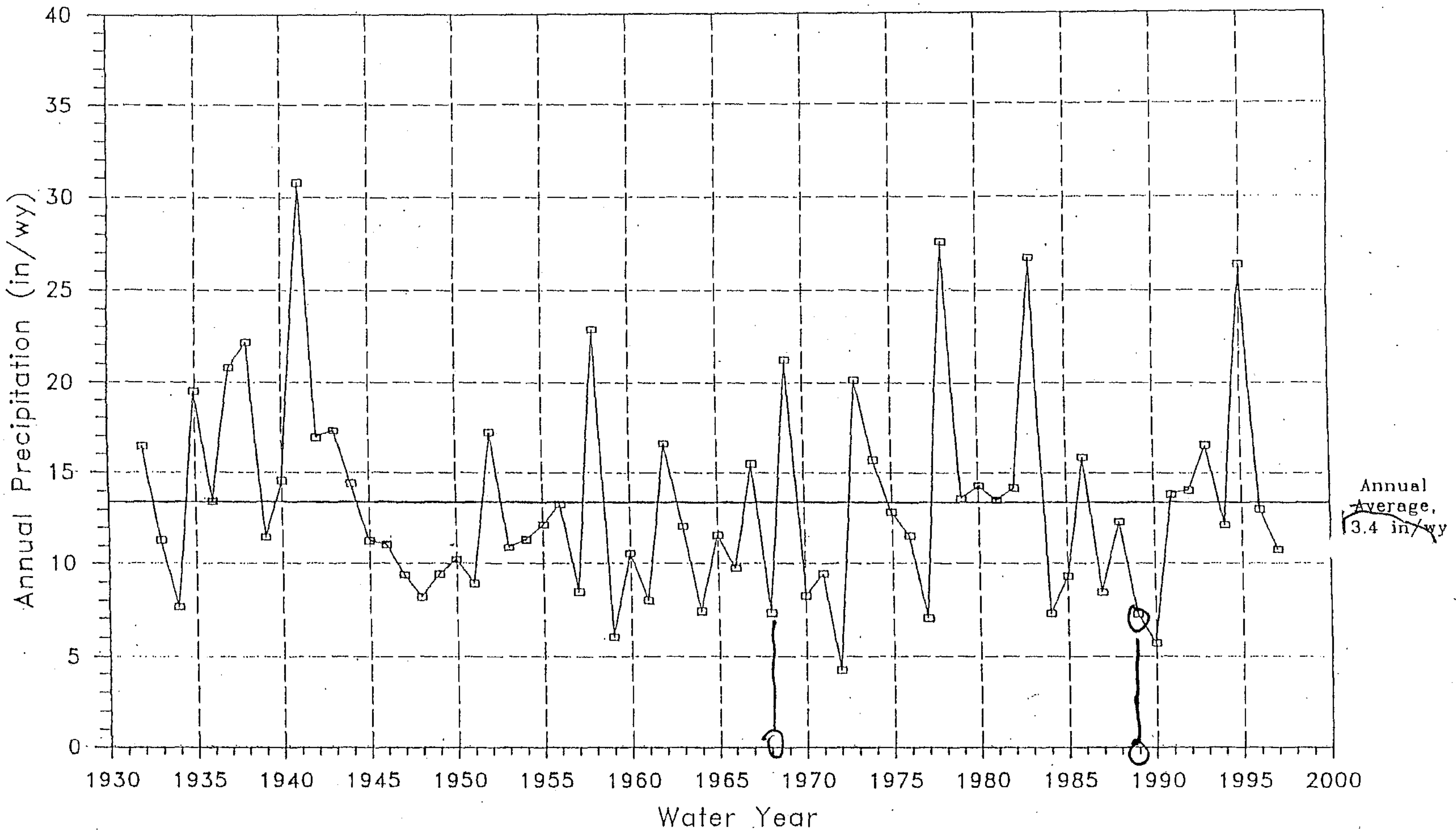

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Figure 3-15
Historical Precipitation, Santa Maria Airport Gauge
Santa Maria Valley Study Area

annual precipitation (Figure 3-16), which indicates that the area has experienced periods of wetter than normal conditions alternating with drier than normal to drought conditions. From the 1930's through 1944, wet conditions prevailed, followed by drier conditions from 1945 through the late 1960's; subsequently, there have been shorter periods of alternating wet and dry conditions, including the most recent cycle of a wet period in the early- to mid-1990's followed by a slightly dry period through 1997. This pattern of fluctuations in climatic conditions closely corresponds to the long-term fluctuations in ground-water levels described in a previous subsection, including the substantial decline observed between 1945 and the late 1960's and the subsequent repeating cycle of decline and recovery between historical low and near historical-high ground-water levels (long-term general stability).

As mentioned at the beginning of this section, the main streams entering the study area are the Cuyama and Sisquoc Rivers; these rivers join in the Valley floor near Garey and become the Santa Maria River, which drains the Valley from this point westward (see Figure 3-14). The headwaters of the Sisquoc River include a portion of the San Rafael Mountains and Solomon Hills, and the River's main tributaries within the study area are Foxen, La Brea, and Tepusquet Creeks. The flows in the Sisquoc River and its tributary creeks are and have been unimpaired throughout the historical period of record. The Cuyama River drains a portion of the Sierra Madre Mountains, including the Cuyama Valley, and the River's flows entering the Valley became controlled following the construction of Twitchell Dam (from 1957 to 1959). In the southern portion of the study area, Orcutt Creek drains a portion of the Solomon Hills and the Orcutt area before ending near Betteravia. Numerous streamflow gauges are or have been located throughout the study area, including on the Cuyama, Sisquoc, and Santa Maria Rivers and Foxen, La Brea, Tepusquet, and Orcutt Creeks. Three gauges were located in the adjacent portion of the headwaters of the Valley on the upper Cuyama River and Huasna and Alamo Creeks, and the releases from Twitchell Dam have been recorded since near the beginning of its operation. It should be noted that a gauge was briefly located in the southern part of the Valley measuring flows in Bradley Canyon; however, these flows originate within and are eventually recharged to the study area and were not considered to be pertinent to the model

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Figure 3-16
Cumulative Departure Curve, Historical Precipitation
Santa Maria Valley Study Area

development. The period of record for the streamflow data that was most pertinent to the model development was from 1944 through 1997.

The gauges on the Sisquoc River, "Near Sisquoc" and "Near Garey", have the most complete records from the early 1940's to the present. The average discharge rate in the River at these gauges is 4.0 and 4.1 million ft^3/day, respectively. A bar chart of the historical annual streamflow at the "Near Garey" gauge illustrates the long-term fluctuation in flows in the Sisquoc River (Figure 3-17). The period of record is shorter for the gauges on the tributaries to the Sisquoc River and it was necessary to "fill-in" portions of the 1944 to 1997 period by estimating the "missing" streamflow records based on developing runoff-to-runoff relationships (i.e., Sisquoc River to each tributary). This approach to estimating the streamflow records was utilized because rainfall-to-runoff relationships were found to be very poor; poor rainfall-to-runoff relationships were reported previously (Thomasson, 1951). The average discharge rates in the tributaries (for the data sets compositing the recorded and estimated streamflows) are as follows: approximately 40,000 ft^3/day on Foxen Creek, 600,000 ft^3/day on La Brea Creek, and 130,000 ft^3/day on Tepusquet Creek. The majority of the flows in these streams typically occurs from January through April, with a minor amount occasionally in December and May.

The period of record for the streamflow in Orcutt Creek, beginning in water year 1983 to the present, was also augmented by estimating the flows between 1944 and 1982; however, this was done based on development of a rainfall-to-runoff relationship (i.e., Santa Maria precipitation to Orcutt Creek streamflow). The resulting correlation coefficient ($R^2 = 0.82$) indicates that there is a strong correlation between the observed data, and this is likely due to the proximity of the Santa Maria precipitation gauge and the Orcutt Creek streamflow gauge, which are less than three miles apart in the southern part of the Valley. The average discharge rate in the Creek is approximately 100,000 ft^3/day, which is small relative to flows in the Sisquoc River and some of its tributaries. The majority of the flow in Orcutt Creek typically occurs over a slightly shorter period from January through March.

Before the construction of Twitchell Dam, flows on the Cuyama River were recorded at a gauge approximately 15 miles upstream of its confluence with the Sisquoc River, and flows in two of its tributaries adjacent to the study area (Huasna and Alamo Creeks) were also recorded (see Figure 3-14). During and following the construction of Twitchell Dam, the flows in the Cuyama River were instead recorded at a gauge below the Dam; the releases from the Dam have also been noted by the dam keeper since about 1962. Thus, the historical period of record for streamflow in the Cuyama River is a composite of the pre-Twitchell records (combined flows in the upper Cuyama River and Huasna and Alamo Creeks) and the post-Twitchell records (flows in the lower Cuyama River, either the direct releases from the Dam or at the gauge below the Dam). Upon reviewing the streamflow data from years of "overlap" of the data, it was observed that the flow recorded at the Cuyama River gauge below Twitchell Dam closely matched the combined flows in the upper Cuyama River and Huasna and Alamo Creeks; also the direct releases from the Dam closely matched the flow recorded at the Cuyama River gauge below the Dam. This indicates that only minor losses in streamflow occurred along these segments of the Cuyama River and that it was appropriate to fill-in the missing record at the gauge below the Dam (1944-1958 and 1983-1997) based directly on the Dam release records or streamflow data from the upper Cuyama River and its tributaries.

A bar chart of the composite streamflow data illustrates the long-term fluctuation in flows (controlled and uncontrolled) in the Cuyama River (Figure 3-18). Based on the composited data, the average discharge rate in the River at the gauge below the Dam is 4.8 million ft^3/day, which is somewhat greater than in the Sisquoc River. The majority of the flows in the upper Cuyama River and its tributaries has typically occurred from November through June, although the flows can be continuous during some wetter years. These flows have been stored in Twitchell Reservoir since approximately 1960 for release into the lower Cuyama River and (further downstream) the Santa Maria River. The Twitchell project is operated to optimize the recharge of water to the Valley along the Santa Maria River; water is typically released between early spring (when flows in the Sisquoc River have subsided) and late fall such that the "wetline" (the downstream edge of flows) is maintained approximately at the Bonita School Road Crossing. Depending on the availability of water in storage

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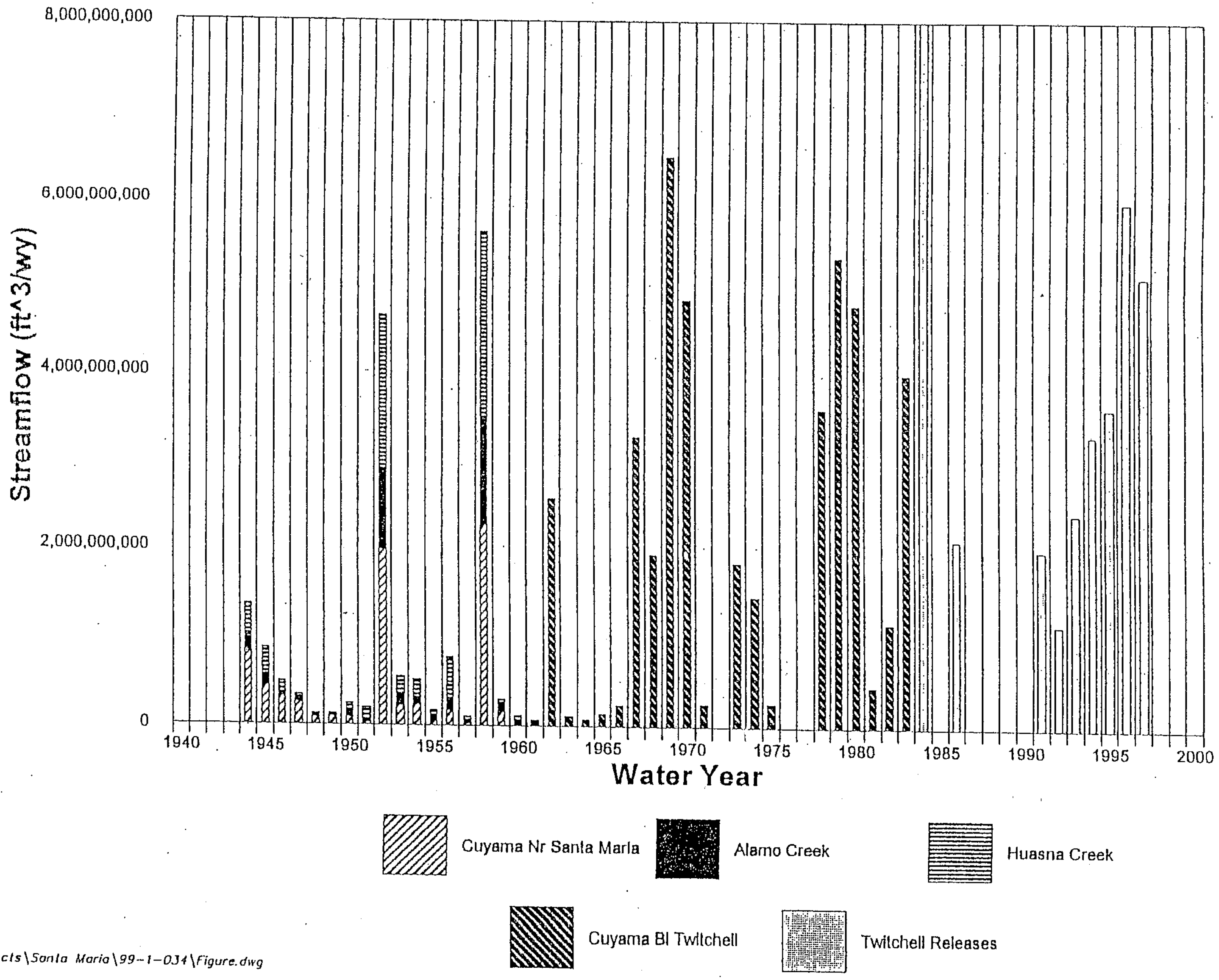

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Figure 3-18
Historical Streamflow, Cuyama River Below Twitchell Dam
Santa Maria Valley Study Area

from year to year, water may not be released for extended periods of time (i.e., during drought years) or may be released continually (i.e., during wetter periods).

The gauge on the Santa Maria River is located in the western part of the Valley at Guadalupe and the average discharge rates at that location (pre-Twitchell and post-Twitchell project) are 3.2 and 2.1 million ft^3/day, respectively. A bar chart of the historical annual streamflow at the Guadalupe gauge illustrates the long-term fluctuation in flows in the Santa Maria River and some indication of the project's effectiveness in increasing the recharge of the flows, which correspondingly reduces the amount of flow to the western part of the Valley (Figure 3-19). The amount of supplemental recharge to the Valley due to the Twitchell project operations is roughly estimated to be 3.8 million ft^3/day or 32,000 acre-feet per water year (af-wy), based on the net loss in streamflow between the Sisquoc River gauge near Garey and the Santa Maria River gauge at Guadalupe (from pre- vs. post-Twitchell project periods). The estimation does not account for changes in climatic conditions between the pre- and post-project periods or losses/gains along the River due to other processes, both of which could result in changes in the amount of water available for recharge over time. Clearly, the supplemental recharge has contributed to maintaining ground-water levels in the Valley, and this is perhaps most visible near the upstream portions of the Santa Maria River where the ground-water elevation contours in post-project contour maps become more or less parallel to the River, as described in a previous subsection. If desired, additional detailed analysis of the beneficial impacts of Twitchell project operations can be conducted as one of several possible scenarios using the numerical ground-water flow model described herein; such a possible scenario,is described in Chapter V below.

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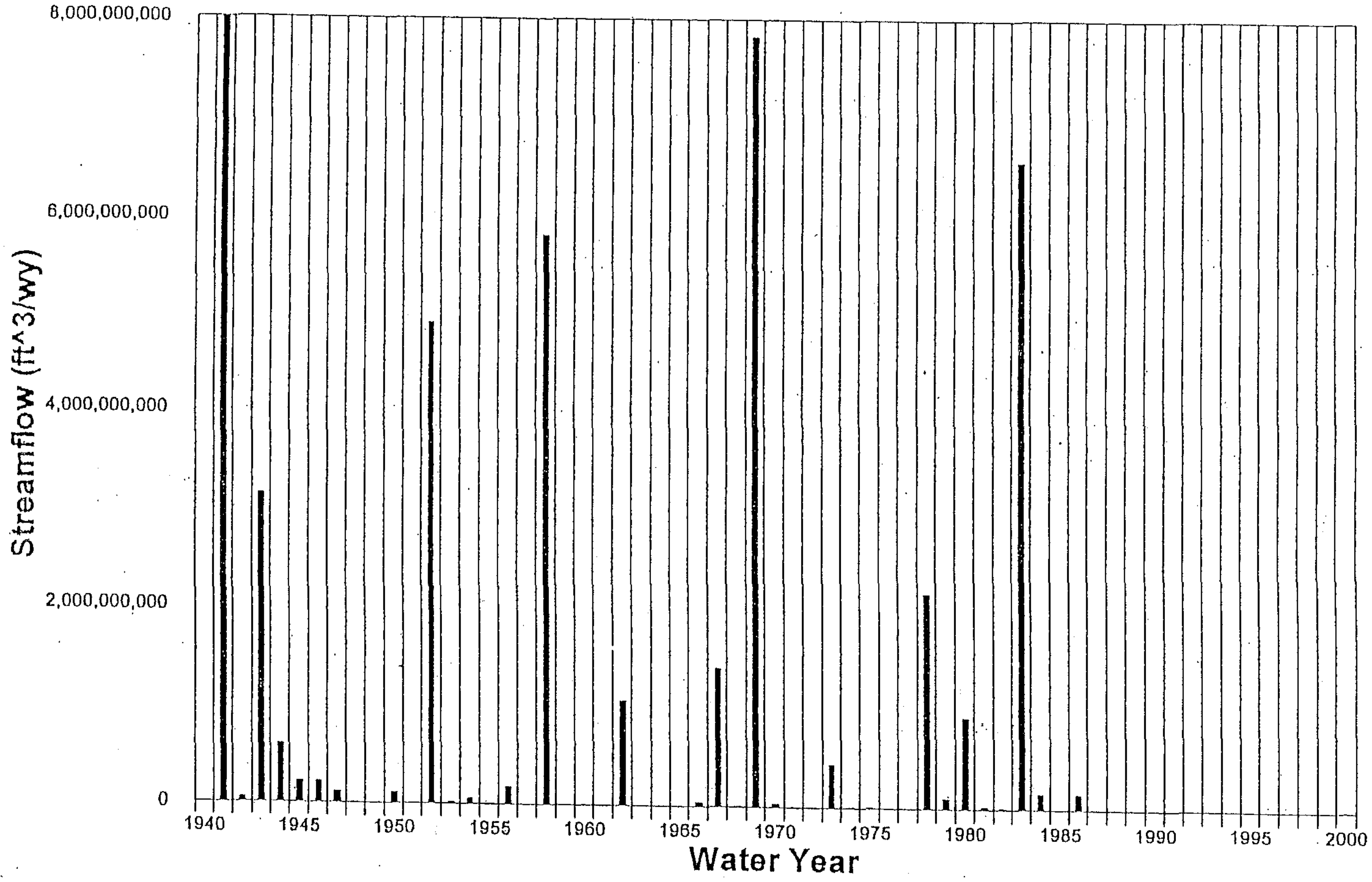

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Figure 3-19
Historical Streamflow, Santa Maria River at Guadalupe
Santa Maria Valley Study Area

IV. Ground-Water Flow Model

A numerical ground-water flow model was developed encompassing the Santa Maria basin that could be used to evaluate the potential ground-water impacts associated with basin management actions that may be taken by the District or other entity within the basin. In addition, it was to be used for estimating the storage and perennial yield in the portion of the basin within the study area. For purposes of this report, the model was used to simulate the aquifer system's response to historical conditions within the basin (historical inflows to and outflows from the study area, and land use changes), calculate the historical changes in storage since the mid-1940's, and provide an estimate of the perennial yield. The conceptualization, development, and calibration of the model are discussed in this chapter, as well as the results of the model sensitivity analysis and water budget review.

A ground-water model can be defined as a simplified version of a real ground-water system that approximately simulates the response of the system to identified hydrologic stresses. The process of developing a ground-water model begins with a conceptual model of the aquifer system. A conceptual model is a description of the characteristics of the ground-water system and includes the occurrence and movement of ground water and a depiction of recharge and discharge stresses. A conceptual model is developed following a review of the geology and hydrology of the area, the interpretation of ground-water inflows and outflows, and an analysis of historical ground-water level data.

The conceptual model is translated into a mathematical model that consists of the governing equations of flow and all pertinent boundary conditions. The mathematical model is then solved through the use of a documented ground-water modeling code. Boundary conditions, aquifer characteristics, and recharge and discharge components are estimated based on available data, and subsequently translated into model input files used to run the model, which in turn generates simulated hydraulic head within the model area over a specified hydrologic time period. The modeling process then enters an iterative stage of calibration, in which the simulated hydraulic heads generated by the model are compared to actual historical ground-water elevation data from the model's hydrologic period. Aquifer characteristics and other parameters used in the model are adjusted in order to cause the model-calculated hydraulic heads to agree, as closely as possible, with the historical data. After calibration is completed, a sensitivity analysis is generally conducted to determine the model's sensitivity to changes in selected input parameters. This provides additional support that the calibrated model values, such as hydraulic conductivity, recharge, and pumpage, are as accurate as possible.

The calibrated model can then be used to predict (simulate) the future response of the ground-water: surface water system to events that change the system and/or the stresses on the system. In addition, the model can be used to simulate the ground-water levels that could have resulted during the model's hydrologic period, had the historical system or stresses been different. For this report, the model was used to simulate the ground-water: surface-water system's response to the historical conditions; specifically, the historical inflows (e.g., precipitation and streamflow recharge), outflows (e.g., agricultural and municipal/industrial pumpage), and changes in land use (i.e., the distribution or location of these stresses). The model was then used to estimate the historical changes in storage and the yield of the aquifer system in the portion of the basin within the study area.

Conceptual Model

The conceptual model is developed by formulating a set of assumptions about the real ground-water system that reduce the system and its inherent complexities, all of which cannot be simulated, to a simplified version that can be evaluated quantitatively and is acceptable in view of the objectives of an investigation. In addition, data limitations that have made it necessary to estimate model parameters are identified. A description of the conceptual model developed for the study area is provided below, including the following:

- aquifer system geometry and characteristics
- hydrologic boundaries
- surface water-aquifer interactions
- sources and sinks
- data limitations
- summary of simplifying assumptions

The conceptual model was developed from a review and interpretation of many sources of information, including reports with information about the geology, hydrology, and aquifer characteristics; lithologic logs from Well Drillers' Reports; historical ground-water level and stream stage and flow data; aquifer and pump test data; crop survey maps; precipitation, evaporation, and evapotranspiration data; and ground-water pumpage information (estimated agricultural and recorded municipal/industrial).

Aquifer System Geometry and Characteristics

The model encompasses the entire Santa Maria basin and the active portion of the model surrounds the study area: specifically, the contiguous area of the Santa Maria and Sisquoc plains, the Orcutt upland, and the southern portion of the Nipomo Mesa (south of Black Lake Canyon) (see Figure 2-1). It is generally bounded by the Casmalia and Solomon Hills to the south, the San Rafael Mountains to the southeast, the Sierra Madre Mountains to the east and northeast, the remaining portion of the Nipomo Mesa to the north, and the Pacific Ocean to the west. All of the aquifers within the basin are simulated in the model, including those comprised of the Quaternary Alluvium, Orcutt Fm., Paso Robles Fm., and the Careaga Sand, which collectively underlie the majority of the basin; the portion of aquifer system in the terrace deposits along the northeast edge of the Sisquoc plain are also simulated in the model. The base of the aquifer system is defined by the base of the Careaga Sand, the lowermost fresh water-bearing formation in the basin. A small portion of the consolidated rocks (Foxen Mudstone, Sisquoc Fm., Monterey Shale, and Franciscan Fm.) comprising the hills along the southern edge of the Valley is also simulated in the model in order to provide sufficient thicknesses of the formations comprising the basin aquifers (which in reality taper down to feather edges along the flanks of the hills).

The basin aquifer system was divided into six layers for modeling purposes. The composition of the two uppermost model layers varies throughout the study area, reflecting the different areal extent of each geologic formation, as described in the **Hydrogeologic Conditions** section. The uppermost layer of the model, layer 1, consists of the upper members of the Quaternary Alluvium and Orcutt Fm., which are juxtaposed next to each other (and are similar in thickness) and collectively comprise the majority of the Valley floor and Orcutt Upland. In the Nipomo Mesa area, where the uppermost aquifer instead consists of the Paso Robles Fm. (the upper Quaternary Alluvium is truncated along the southern edge of the Mesa), layer 1 is comprised of the Paso Robles Fm. Along the northeast edge of the Sisquoc plain, where the uppermost aquifer instead consists of terrace deposits (the upper Quaternary Alluvium is truncated along the southwestern edge of the terraces), layer 1 is comprised of the terrace deposits. Along the southern edge of the Orcutt Upland, where the upper Orcutt Fm. is truncated (as is the lower Orcutt Fm.) and the underlying Paso Robles Fm. tapers to a feather edge, layer 1 is comprised of the Paso Robles Fm. and the consolidated rocks. Layer 2 of the model consists of the lower members of the Quaternary Alluvium and Orcutt Fm., which are also juxtaposed next to each other (and are similar in thickness) and collectively underlie the majority of the Valley floor and Orcutt Upland. As was the case for layer 1, layer 2 is comprised of the Paso Robles Fm. in the Nipomo Mesa area and the Paso Robles Fm. and consolidated rocks along the southern edge of the Orcutt Upland. Along the northeast edge of the Sisquoc plain, the terrace deposits are only as thick as the adjacent upper member of the Quaternary Alluvium (layer 1) and layer 2 is comprised of the Paso Robles Fm.

Although the Paso Robles Fm. and Careaga Sand essentially behave as a single aquifer, they were divided into four layers for modeling purposes (layers 3 through 6). The layers are progressively thicker with depth: specifically, approximately twice the thickness of the overlying layer (e.g., layer 3 is twice as thick as layer 2, layer 4 is twice as thick as layer 3, and so on). This "telescoping" of layer thicknesses, with each limited to twice that of the overlying layer, was necessary in order to maintain stable ground-water flow conditions within the model. As a result, layers 1 and 2 generally range in thickness between 60 feet in the Nipomo Mesa and southeast part of the Sisquoc plain, 100 feet beneath Orcutt, and 130 feet at the coast. This reflects the gradual thickening of the Quaternary Alluvium and Orcutt Fm. from the eastern Valley toward the coast. Layer 3 ranges in thickness between 40 feet in the Nipomo Mesa and Sisquoc plain, 80 feet at the coast, and 150 feet beneath Orcutt; and layers 4 through 6 are each approximately twice the thickness of the overlying layer, with the thinnest portions beneath the Nipomo Mesa and Sisquoc plain and the thickest portions beneath Orcutt. The composite thickness of layers 3 through 6 ranges between 500 to 700 feet around the edges of the model and 2,200 feet beneath Orcutt, reflecting the folding of the Paso Robles Fm. and Careaga Sand into a trough with the deepest portion beneath the Orcutt area. A schematic cross section illustrates the model layers and other aspects of the conceptual model (Figure 4-1).

For the model, the aquifer characteristics (hydraulic conductivity values) of the different formations were based primarily on the results of aquifer or pump tests; this was the case for the lower Quaternary Alluvium (part of layer 2) and the Paso Robles Fm. (primarily layers 3 through 6). The aquifer characteristics for the Careaga Sand (the lower portion of layer 6) were based on laboratory permeability tests. These aquifer, pump, and laboratory tests were described in the **Hydrogeologic Conditions** section. However, such test results were not available for all the formations, including the upper Quaternary Alluvium (part of layer 1), the Orcutt Fm.(part of layers 1 and 2), the terrace deposits (a minor part of layer 1), or the consolidated rocks (minor parts of layers 1 and 2). In these cases, the characteristics were estimated based on the lithologic descriptions of the formations or typical literature values for the respective type of deposit. Vertical hydraulic conductivities of the aquifers were assumed to be one-tenth of the horizontal hydraulic conductivities, and the vertical hydraulic conductivities of the river channel deposits were based on the in-situ permeability tests described in the **Hydrogeologic Conditions** section.

For modeling purposes, layer 1 was designated as an unconfined aquifer; layers 2 and 3 were unconfined to confined aquifers; and the remaining layers were confined aquifers. These designations were selected based on knowledge of the aquifer characteristics and historical ground-water level fluctuations. Layer 1 was designated as an unconfined aquifer because the layer 1 formations comprise the water table aquifer in the study area (and in large areas, the upper Orcutt Fm. aquifer of layer 1 is typically unsaturated). Layer 2 was designated as an unconfined/confined aquifer because the lower Quaternary Alluvium aquifer of layer 2 is unconfined in the eastern to central part of the study area, but transitions to confined conditions in the western part. In addition, in some areas, portions of the lower Orcutt Fm. aquifer of layer 2 have dewatered during historical dry period conditions (i.e., ground-water levels have declined below the top of layer 2). Layer 3 was designated as an unconfined/confined aquifer because, in some areas, the upper portion of the Paso Robles Fm. aquifer of layer 3 has also dewatered during historical dry period conditions. Layers 4, 5, and 6 were designated as confined aquifers because, even though the Paso Robles Fm. and Careaga Sand primarily behave as one single unconfined aquifer, they have remained saturated during the historical period.

Hydrologic Boundaries

Ground-water flow in the study area originates in its southeast portion from recharge from the upstream part of the Sisquoc River and its tributaries and from the upstream part of Orcutt Creek (see Figures 3-10, 3-11, and 3-12). Ground water within the study area has historically flowed primarily to the west-northwest with essentially no inflow from or outflow to the surrounding hills and mountains and Black Lake Canyon. Outflow from the study area occurs along the coast; landward flow (from the ocean toward the Valley) has not occurred, based on historical ground-water elevations. The model was designed such that the horizontal flow of ground water (inflow or outflow) does not occur across most of the model boundaries, with the exceptions of Black Lake Canyon and the coast. Even though ground water has historically flowed toward the west-northwest across the southern Nipomo Mesa with minimal to no horizontal flow across the Black Lake Canyon area (north-to-south or vice versa); the model was designed to allow horizontal flow to occur across this model boundary, should conditions arise (e.g. changes in ground-water levels on either side) that would induce flow from or toward the northern Mesa. The model was also designed to allow horizontal flow across the coastal boundary, in either a coastward or landward direction. The base of the model domain (the base of layer 6) was designated as the base of the Careaga Sand, the lowermost fresh water-bearing formation in the study area.

Surface Water-Aquifer Interactions

The ground-water system in the study area is strongly influenced by streamflow in the Sisquoc, Cuyama, and Santa Maria Rivers, by the tributaries to the Sisquoc River, and by Orcutt Creek, all of which typically act as sources of recharge to the aquifer. Discharge from the aquifer (gaining stream conditions) has historically occurred in the area near the mouth of the Santa Maria River to a limited extent. Gaining or losing stream conditions in the study area are determined by the hydraulic gradient between the rivers (and creeks) and the ground-water system, which can change due to factors such as precipitation and surface water releases to the Cuyama (and, therefore, the Santa Maria River). Flow between the aquifer and these streams is simulated in the model and, for the hydrologic period selected for the model, the streams are primarily losing streams. Also, as noted in the previous subsection, ground water historically flowed from the aquifer system to the ocean, and this flow is simulated in the model as well.

Sources and Sinks

Recharge to and discharge from the ground-water system are simulated as source and sink terms, respectively, in the model. The source or recharge components include precipitation; treated municipal waste water and processing water applied to land; irrigation return flows; and flow from the stream system (under losing conditions). The sinks (discharge components) include ground-water pumpage (agricultural, municipal, industrial, and domestic); evapotranspiration (ET); flow to the stream system (under gaining conditions); and ground-water outflow to the ocean.

The precipitation simulated in the model was based on the historical precipitation recorded at the closest station, "Santa Maria-Airport". The agricultural pumpage simulated in the model was estimated from historical land use maps, measured ET of applied water (ETaw), precipitation records, soil types, and reported irrigation efficiencies. The agricultural pumpage was estimated because the number, location, and pumping rates of agricultural wells in the study area are not fully known. The municipal pumpage simulated in the model was based on historical pumpage records from Santa Maria, Guadalupe, Nipomo, and the Southern California Water Company (CalCities). Industrial pumpage from the UnoCal refinery, the Union Sugar refinery, and the PictSweet facility was based on reported amounts available for various time periods. The amount of individual domestic pumpage in the valley was assumed to be insignificant relative to pumpage for irrigation, municipal, and industrial uses. The volume of treated municipal waste water and processing water applications were estimated based on summary reports filed with the Central Coast Regional Water Quality Control Board (CCRWQCB) available for selected time periods; the return flows from these applications simulated in the model were estimated based on the method and location of application. The irrigation return flows were based on the reported soil types and irrigation efficiencies.

Data Limitations

There are a number of data limitations within the model area that have made it necessary to estimate some model parameters using limited data. These limitations are not considered to have an adverse effect on the objectives of the modeling analysis because the estimated values have been adjusted during the calibration process. One limitation is the lack of well construction (screen interval) information for many wells with historical ground-water level data, which was needed to fully qualify these data by aquifer in the basin, and thus, fully characterize ground-water levels and flow patterns within each aquifer.

Aquifer, pump, and/or laboratory test data, from which aquifer characteristics were calculated or estimated, were available from numerous wells throughout the study area for the principal aquifer formations (lower Quaternary Alluvium, Paso Robles Fm., and Careaga Sand), but not for the upper

Quaternary Alluvium, Orcutt Fm., Older Dune Sand, terrace deposits, or consolidated rocks. As a result, it was necessary to estimate their hydraulic conductivity values for modeling purposes.

Ground-water pumpage from agricultural and individual domestic wells in the model area is not metered or otherwise recorded and the agricultural pumpage was estimated as described in the previous subsection; individual domestic pumpage was assumed to be insignificant. Complete historical records of the volume of industrial pumpage and treated waste water/processing water applications were not available, and it was necessary to estimate these volumes, as well as the percentages of each that have returned to the basin as recharge.

The records for ET data (e.g., potential ET or reference ET) were available for only short periods of time during the historical period. These data were needed for estimating the agricultural pumpage simulated in the model. As a result, summary estimates of ET_{aw} (by crop, growing season, and amounts of effective precipitation) based on ET measured during selected periods during the 1960's and 1970's in California's central coastal valleys were used to estimate the pumpage

Summary of Simplifying Assumptions

The most important assumptions used in the development of the conceptual model are summarized as follows:

1. The aquifer system, which is composed of the alluvial deposits described in the **Hydrogeologic Conditions** section, can be represented by six layers: an upper unconfined layer, two unconfined/confined layers, and three confined layers at depth. The layers have different aquifer properties based on the formations comprising them.

2. Ground-water flow within each layer is horizontal. Flow between the layers is vertical. Horizontal and vertical flow into or out of the aquifer system to the surrounding consolidated rock was neglected because it is small relative to other components of ground-water flow.

3. Ground water enters the model primarily from the losing reaches of the Sisquoc River and its tributaries, as well as from Orcutt Creek, in the southeast part of the model; ground water also enters the model from the areal infiltration of precipitation, areal irrigation return flows, and localized application of treated municipal waste water and processing water. Ground water exits the model along the coast across the western model boundary, through minor gaining reaches of the Santa Maria River, and through ground-water pumpage and ET losses.

4. The horizontal hydraulic conductivity of the aquifer is assumed to be heterogeneous and isotropic (varying with distance but not with direction). Vertical hydraulic conductivity (in all areas except the streambeds) was assumed to be one-tenth of the horizontal hydraulic conductivity. The storage coefficients in layers 2 and 3 are assumed to vary between a confined storativity and unconfined specific yield value, depending on the model-calculated hydraulic head. If the head drops below the top of these layers, they become unconfined and specific yield values are applied. The three lowermost layers (layers 4, 5, and 6) are assumed to be confined under all conditions.

5. Flow between the main streams and the aquifer is simulated by the model; an accounting of flow volumes in the streams is made by the model, and the stream stage is calculated by the model based on the flow volume accounting. Streamflow entering the model is assumed to be instantly available to downstream reaches during each stress period, and leakage between the streams and aquifer is assumed to be instantaneous.

6. Agricultural ground-water pumpage was simulated as areal discharge, primarily from layers 2 through 4 of the model, because exact well locations and pumping rates are not completely known.

7. Storage in the aquifer materials responds instantaneously to changes in hydraulic head.

For the purposes of this analysis, these simplifying assumptions are considered reasonable and do not prevent the model from predicting the approximate magnitude of ground-water impacts resulting from various possible basin management actions.

Model Development

The process of converting the conceptual model described above into a numerical model involves the selection of a modeling code, construction of a model grid, selection of boundary conditions, designation of input parameters, and preparation of model input files. A detailed discussion of the development of the numerical model is provided below.

The Santa Maria Valley ground-water flow model uses a three-dimensional finite-difference modeling code called MODFLOW (McDonald and Harbaugh, 1988). The modeling code was written by the U.S. Geological Survey and is the most widely used numerical model in the ground-water profession. It uses a variety of subroutines, called "packages", to simulate different ground-water flow components such as areal recharge, pumpage, and flow to and from streams. In order to run the model, input data files are prepared for each package used in the simulation. A finite-difference model such as MODFLOW requires that the flow system be subdivided, or discretized, by dividing the volume of the model into a rectangular grid of columns, rows, and layers so that the governing equations of ground-water flow can be solved for each cell of the grid. Hydraulic properties within each cell are assumed to be constant. The model calculates the hydraulic head in each cell and the rate of flow between cells.

The model was developed to simulate transient conditions whereby ground-water levels and flow can vary with time. Discretization over time is accomplished by dividing the continuous time domain (the hydrologic period of the model) into specific time intervals known as stress periods. Model inputs that vary with time, including recharge and discharge, streamflow, and hydraulic head along the northern model boundary, must be estimated for each stress period. The hydrologic period selected for the model was a 53-year period between Fall 1944 through Spring 1997. This period was selected to encompass significant events in the historical development of the basin, including an increased demand on ground-water resources and the enhancement of recharge to the basin from operation of the Twitchell project, as well as several alternating cycles of wet and dry hydrologic conditions. Ground-water levels at the beginning and end of the hydrologic period are similar, approaching near historical-high levels, so that the long-term change in basin storage is minimized. The hydrologic period was also selected to encompass the period of record for ground-water level data for a sufficient number of wells and the period of record for streamflow data for the main streams in the study area. Semi-annual stress periods (6 months in length) were selected so that the model's response to seasonal fluctuations caused by factors such as precipitation, irrigation, and streamflow could be determined.

Model Grid and Boundary Conditions

The model grid consists of six layers with dimensions of 90,000 feet by 180,000 feet (approximately 17 miles by 34 miles) divided into 90 columns and 45 rows (Figure 4-2). The cells are uniform in size throughout the model grid, with dimensions of 2,000 feet by 2,000 feet. The cell thicknesses are variable in each layer, ranging between 60 and 130 feet in layer 1 and between 250 and 1,200 feet in layer 6.

There are true hydrologic boundaries within the model area, specifically along the southern, southeastern, and eastern edges of the study area; no boundary to flow exists along the western edge (the coastline) or northern edge (Black Lake Canyon) of the study area. The overall dimensions of the grid, however, were made large enough so that the model boundaries would not affect the simulated changes in ground-water levels. All model boundaries except the western and northern ones were designated as no-flow cells that do not allow horizontal flow across them into or out of the model grid. This reflects the essentially impermeable nature of the consolidated rocks that define these portions of the basin (and model) boundaries.

The western boundary was designated as constant head cells that allow a hydraulic head to be specified for each cell and held constant throughout the simulation (in this case, at an elevation near sea level). These cells allow horizontal flow across the boundary into and out of the model grid as a function of the hydraulic conductivity and simulated head in adjacent model cells. For example, if the simulated head in the adjacent model area is above sea level, ground water will exit the model across the constant head cells, simulating the historical outflow from the basin to the ocean; alternatively, if the simulated heads decline below sea level, water will enter the model across the constant head cells, essentially simulating conditions of sea water intrusion.

The northern boundary was designated as general head cells that allow a hydraulic head to be specified for each cell (but not held constant throughout the simulation). These cells allow horizontal flow across the boundary into and out of the model grid as a function of the hydraulic conductivity and simulated head in adjacent model cells. The hydraulic heads specified for the general head cells for each stress period were based on the historical ground-water levels near the boundary (estimated from water level hydrographs of nearby wells and water level contour maps constructed for various times throughout the model's hydrologic period (see Figures 3-10, 3-11, and 3-12).

Aquifer Properties

Aquifer properties that were estimated for input into the model include horizontal and vertical hydraulic conductivity, storativity, and specific yield. As described in the previous chapter, the aquifer characteristics of the different formations were designated based primarily on aquifer, pump, and laboratory permeability test results, and in some cases on the relative lithologies between formations, typical literature values, and reported average values (specific yield). The values of the aquifer characteristics initially entered into the model were later adjusted during the model calibration process in order to match (as closely as possible) model-calculated hydraulic head to the historical observed ground-water levels. Other inputs required by the model are the top and bottom elevations of each layer so that the transmissivity of each cell can be calculated (from the hydraulic conductivity and saturated layer thickness). These layer elevations were based on the review of available Well Drillers' Reports and cross sections, as described in the **Hydrogeologic Conditions** section.

Each layer of the model was divided into a number of hydraulic conductivity zones with different ranges of values so that the initially-specified values could later be adjusted during calibration for groups of model cells with similar hydrogeologic characteristics. The distribution of hydraulic conductivity zones was based on the distribution of the known values at different well locations (see Figure 3-13). The zonation reflects the variability of lithologies throughout the model area (e.g., the gradual fining of the formations from east to west, the gradual fining of the alluvial deposits away from the stream courses) and between the different aquifers (e.g., the coarser sediment of the Quaternary Alluvium compared to the more "clayey" Paso Robles Fm.). During calibration, the initial hydraulic conductivity values for the zones in each layer were adjusted to a minor extent. The hydraulic conductivity zonation for each layer is shown on a map of the study area (Figures 4-3, 4-4, and 4-5) and the calibrated values for each zone are presented in Table 4-1.

It was necessary to show zones consisting of fixed ranges of hydraulic conductivity values (as opposed to zones with single values) because approximately 40 values have been designated throughout the model. The resulting calibrated values for the layers ranged from 500 to 4,100 gpd/ft^2 in layer 1 (minor areas were 10 to 225 gpd/ft^2), from 750 to 4,100 gpd/ft^2 in layer 2 (minor areas were 10 to 225 gpd/ft^2), and from 10 to 500 gpd/ft^2 in layers 3 through 6; the higher values were generally along the course of the streams, with smaller values toward the edges of the model area. The vertical hydraulic conductivity throughout the model area was initially assumed to be one-tenth of the horizontal hydraulic conductivities. During calibration, the values changed according to the adjustments in horizontal hydraulic conductivity, but the ratio of vertical to horizontal hydraulic conductivity (one-tenth) was not changed. The storage coefficients originally assigned to the model layers were modified only slightly during calibration; the values averaged approximately 0.0001 for storativity and 15 % for specific yield. The hydraulic conductivity and storage coefficient values for the Nipomo Mesa are in general agreement with the calibrated values from a previous ground-water flow model for the Mesa (Cleath & Associates, 1996).

Table 4-1

Calibrated Hydraulic Conductivity Values for all Model Layers

Zone Number	Horizontal Conductivity (gpd/ft^2)	Vertical Conductivity (gpd/ft^2)
1	10 - 40	1 - 4
2	40 - 75	4 - 8
3	75 - 150	8 - 15
4	150 - 225	15 - 22
5	225 - 375	22 - 38
6	375 - 500	38 - 50
7	500 - 750	50 - 75
8	750 - 1,100	75 - 110
9	1,100 - 1,500	110 - 150
10	1,500 - 2,250	150 - 225
11	2,250 - 3,000	225 - 300
12	3,000 - 4,100	300 - 410

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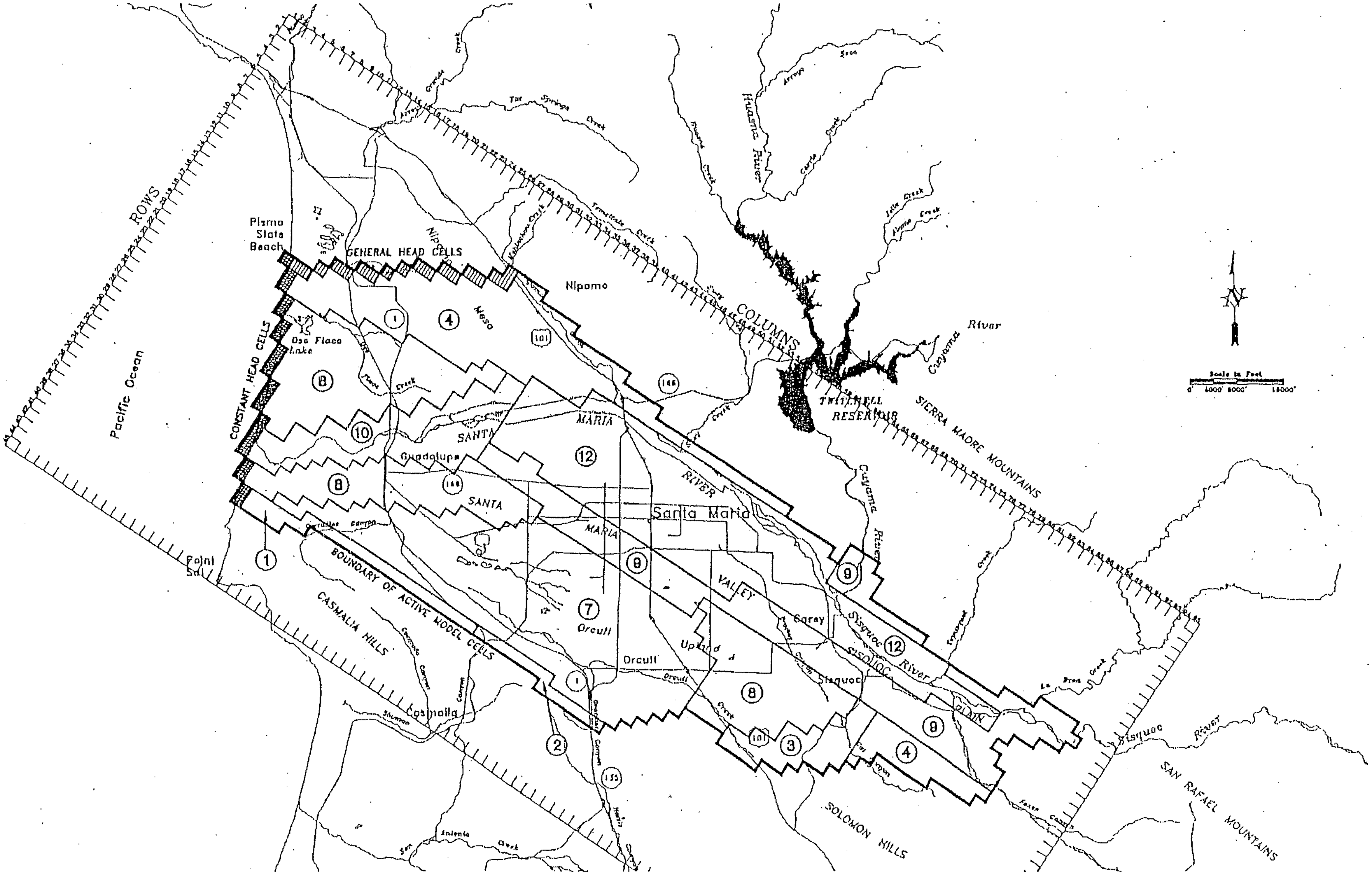

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Figure 4-3
Distribution of Hydraulic Conductivity Zones, Layer 1
Santa Maria Ground-Water Model

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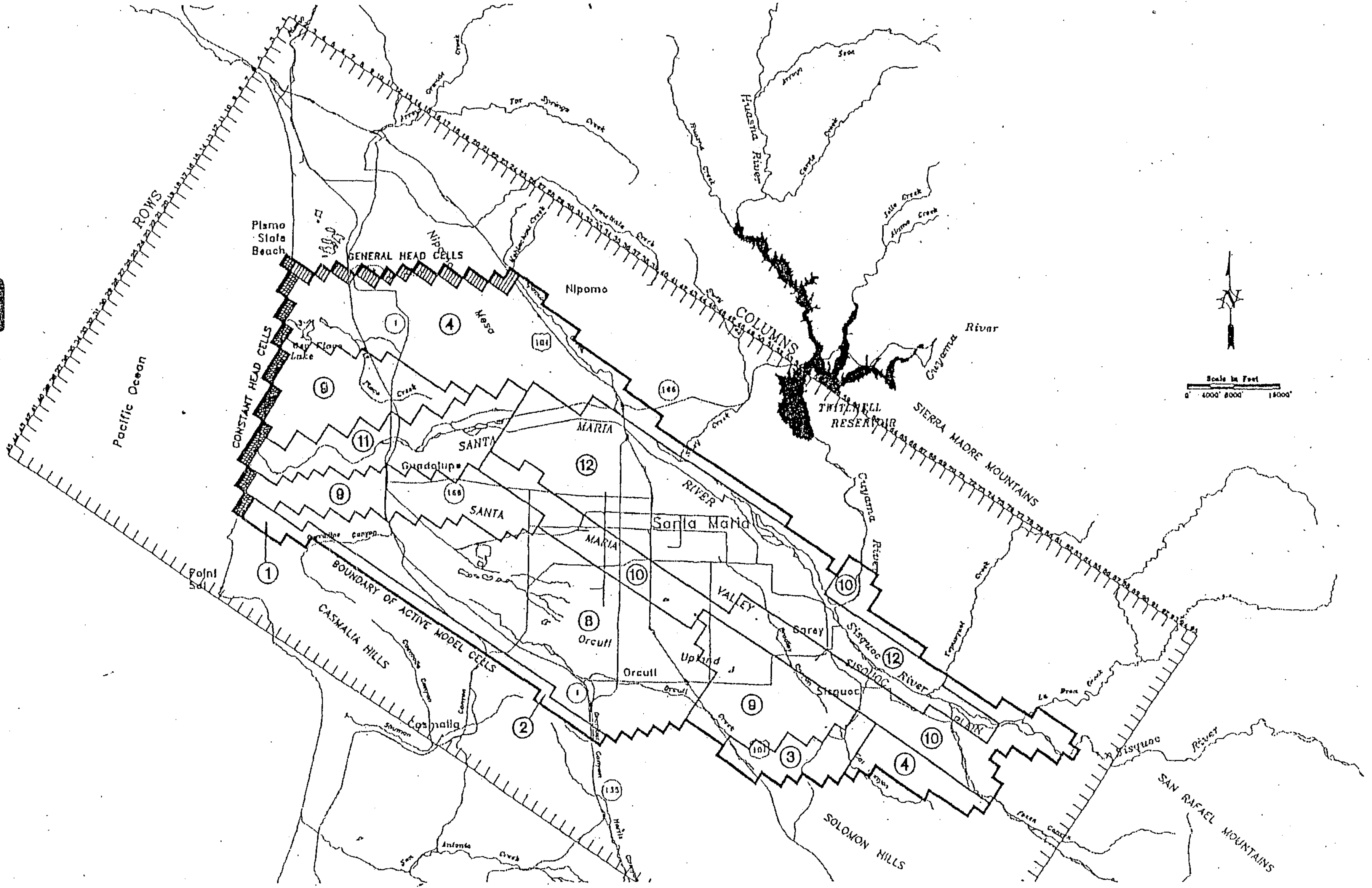

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Figure 4-4
Distribution of Hydraulic Conductivity Zones, Layer 2
Santa Maria Ground-Water Model

west of Orcutt) and the river package provides a method for simulating streams when the flow information is limited.

Parameters required by the streamflow routing package are the streambed elevation and dimensions (width and length) for each stream cell (estimated from U.S. Geological Survey 7-1/2' topographic quadrangle maps); this enables the model to calculate the stream stage in each stream cell, based on the streamflow entering the cell, and determine the relative heads between the stream and aquifer. The package also requires vertical hydraulic conductivity values and thicknesses of the streambed materials; the hydraulic conductivity values used in the model were based on the reported values from in-situ permeability tests at various points along the stream system (Worts, 1951) and the streambed thickness was assumed to be two feet. The model uses the streambed dimensions, vertical hydraulic conductivity, and thickness designated for each stream cell to calculate streambed conductance terms, which are used by the model (in conjunction with the relative hydraulic head between the stream and aquifer) to calculate the leakage from or to the aquifer. The streambed conductance is calculated as the product of the streambed vertical hydraulic conductivity, the length of the stream in a cell, and the width of the stream in a cell, divided by the streambed thickness. Adjustments to the conductance terms were made during model calibration in order to provide an improved match between the observed and simulated ground-water levels in the adjacent aquifer. The calibrated conductance terms in the stream system cells ranged from 22,000 to 425,000 ft^2/day with a streambed thickness of one foot. The highest conductance values were located along the central portion of the main stream system, between the town of Sisquoc and the eastern part of the City of Santa Maria; these values gradually declined toward the ocean.

The parameters required by the river package are very similar to the streamflow routing package and they include streambed elevation and those parameters necessary to calculate conductance terms for each river cell along Orcutt Creek. The river package was used in a manner that simulated a flux of water, specifically the flows in Orcutt Creek, to the aquifer system during each stress period. The streambed vertical hydraulic conductivities and thicknesses were similar to other streams in the study area and the conductance terms were not modified during model calibration.

Discharge and Recharge

The discharge components simulated in the model are pumpage and evapotranspiration; the pumpage included amounts for irrigation, municipal, and industrial purposes. Water used for these purposes has historically, throughout the model's hydrologic period (1944 to1997), been derived solely from ground water. The irrigation pumpage throughout the model's hydrologic period was estimated by first determining the land use patterns during that period: specifically, the acreage and distribution of irrigated and non-irrigated cropland, fallow land, urban areas, and native vegetation areas. This provided a determination of the areas where irrigation (and therefore, pumpage) was conducted over time. Secondly, the distribution of the different irrigated crops grown in the study area (their acreages and locations) was evaluated, as were the reported values of ET of applied water (ET_{aw}) for the crops and the annual rainfall amounts. This provided a determination of the amount of ground water that would have needed to have been pumped over time, solely for the purpose of meeting the water requirements of the different crops. Finally, the reported irrigation efficiencies throughout the study area were evaluated in order to estimate the irrigation pumpage over time (essentially the sum of two components of pumpage: pumpage for meeting the crop requirements plus supplemental pumpage for accommodating the irrigation inefficiencies). A detailed description of each of these steps follows.

Historical land use patterns in the study area were determined from crop survey maps and crop acreage summaries completed by the California Department of Water Resources on approximately ten-year intervals through most of the modeled hydrologic period (available for the years 1959, 1968, 1977, 1985, and 1995). For the period prior to 1959 (specifically, for the year 1944 at the beginning of the model's hydrologic period), the land use patterns were estimated from reported total acreages for the period between 1930 and 1944 (Worts, 1951). The distributions of irrigated and urban land use during 1959 (the first year when detailed information on crop distributions was available) and 1995 are illustrated on maps of the model area (Figures 4-6 and 4-7). It should be noted that the irrigated acreage included irrigated cropland and fallow land. Comparison of these two maps shows how irrigated areas have, over the model's hydrologic period, expanded into portions of the Orcutt

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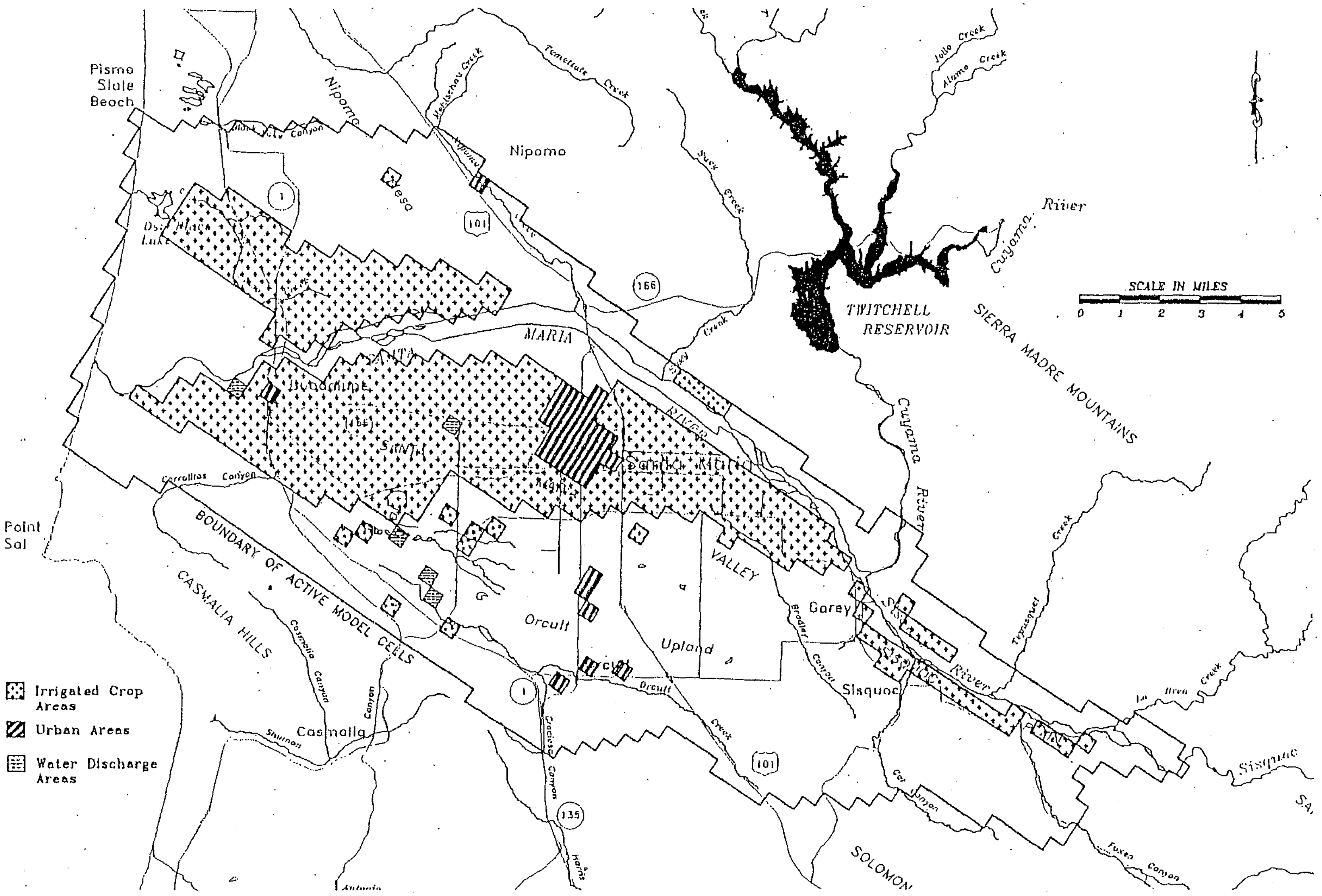

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Figure 4-6
Distribution of Land Use, 1959
Santa Maria Ground-Water Model

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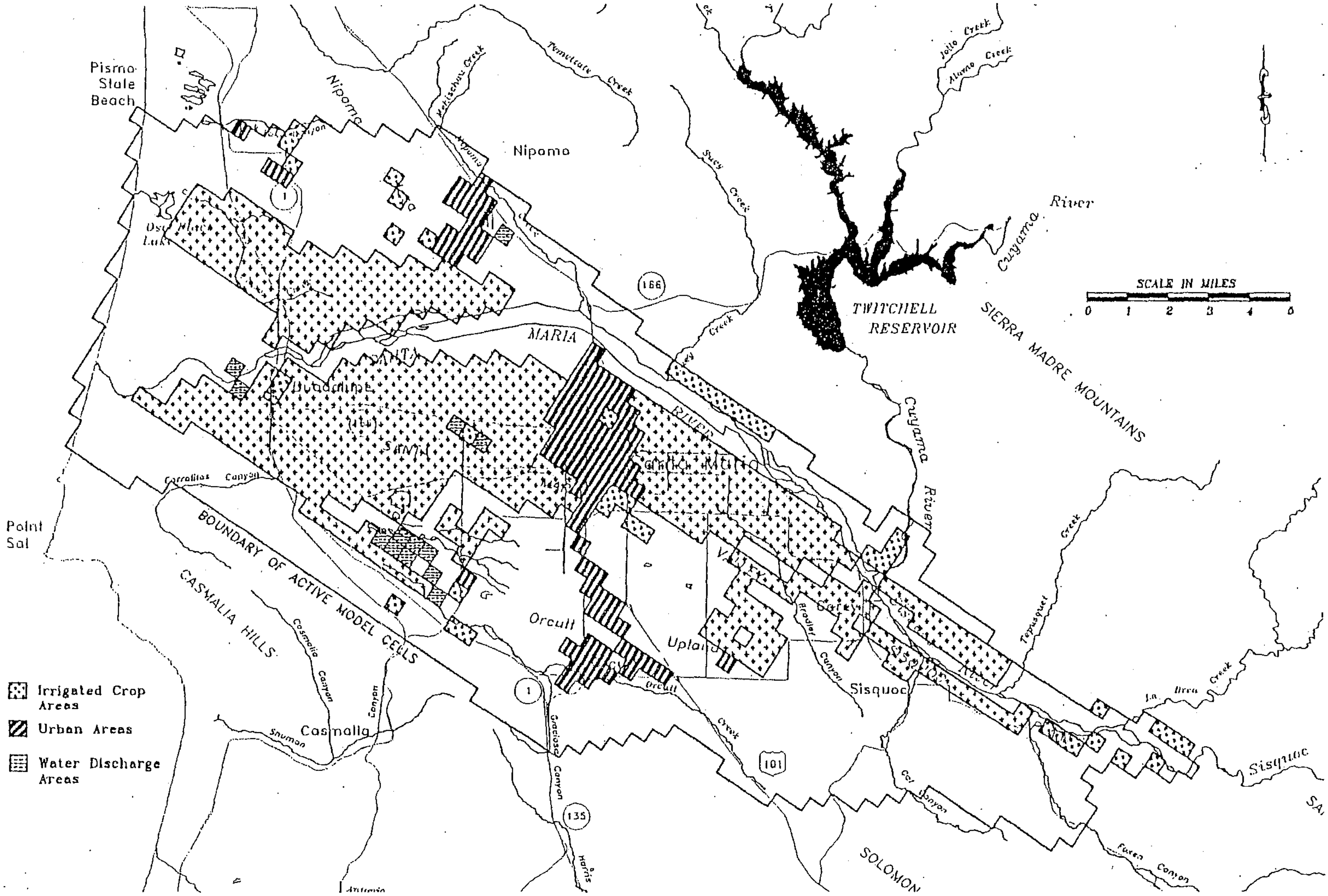

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Figure 4-7
Distribution of Land Use, 1995
Santa Maria Ground-Water Model

Upland, the Sisquoc plain and terraces, the lower Cuyama River floodplain, and the Nipomo Mesa. Minor portions of the irrigated areas have been replaced by urban growth around the southern and eastern margins of the City of Santa Maria.

The distribution of the different irrigated crops grown in the study area (their acreages and locations) was also determined from the crop survey maps and crop acreage summaries listed above, and a bar chart of the crop acreages from each survey year (with the crops grouped by type) shows how the crop types and acreages in the study area have changed over time (Figure 4-8). The most significant change is the increase (more than double) in truck crops grown in the study area. It should be noted that the acreages reported here are "land" acreages; i.e., the land area used for growing crops, regardless of whether it is used for single or multiple cropping throughout any given year. This was done to provide consistency between the earlier acreages derived from technical reports and subsequent acreages from crop surveys. It was also observed that the pattern of cropped parcels is quite dense and highly variable throughout the study area, as well as over time. For purposes of modeling, the irrigated acreages (by crop type) for the years between the crop survey years were estimated by interpolating between the survey years

In order to estimate the pumpage needed to meet the crop requirements, reported values of ET_{aw} for various crop types were reviewed; specifically, these were values measured and developed for different rainfall zones in the central California coastal valleys (DWR, 1975b) that showed how the applied water increased in zones with less rainfall and vice versa. A review of the reported values for the different crops would indicate that they accommodate multiple cropping. These values were used to develop a relationship between ET_{aw} values and the annual rainfall amounts within the study area by crop type (Figure 4-9). The ET_{aw} values are in general agreement with ET values estimated for a previous study of the Santa Maria Valley's ground-water resources (Toups Corporation, 1976). The ET_{aw} for each crop type (for the appropriate annual rainfall amount) was multiplied by the acreage of each crop type for each year to calculate the annual pumpage associated with each crop type's acreage; each of these pumpage amounts was then summed to calculate total annual pumpage for the model area. These estimated annual pumpage amounts (for meeting the crop water requirement)

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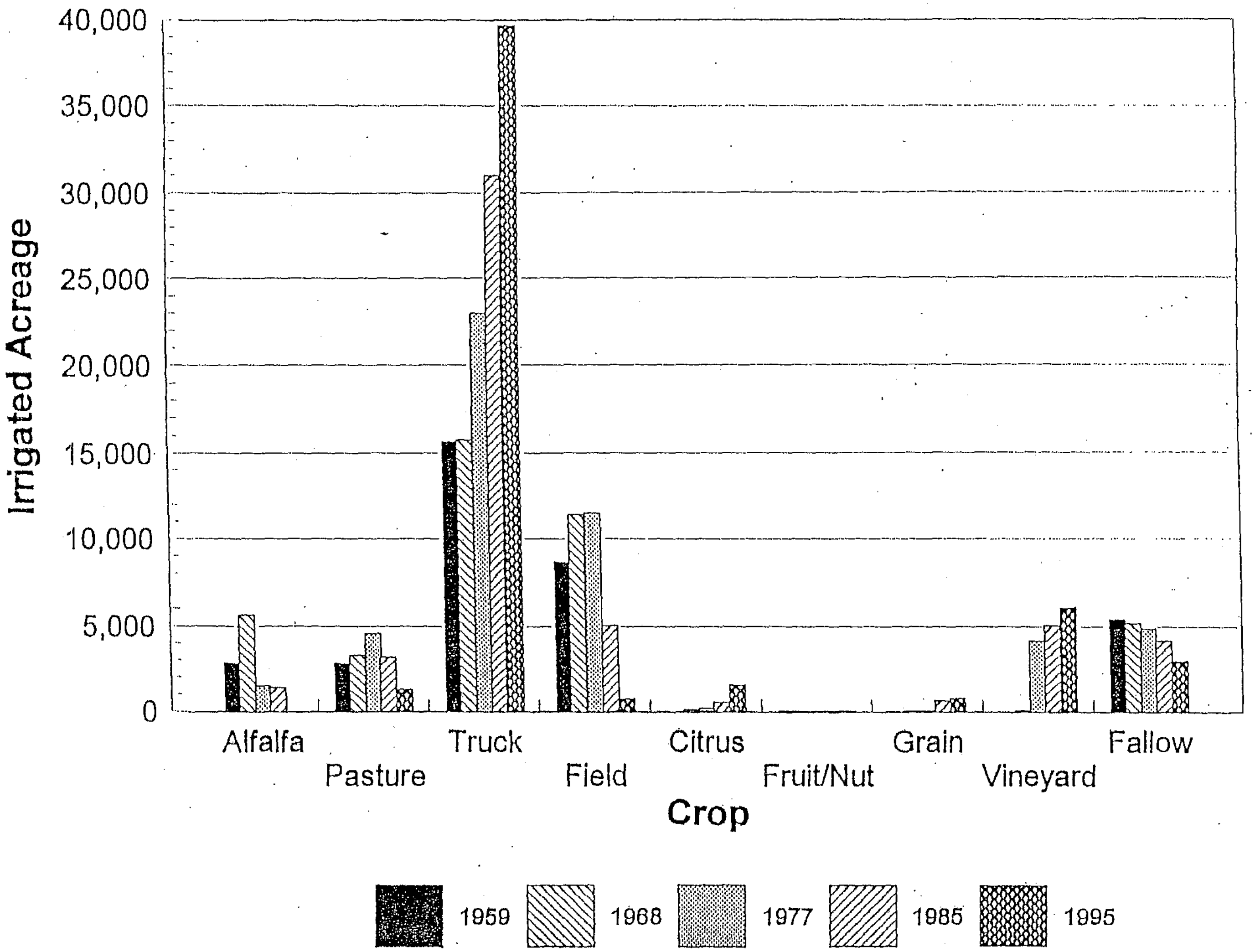

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Figure 4-8
Historical Distribution of Irrigated Acreage by Crop
Santa Maria Valley Study Area

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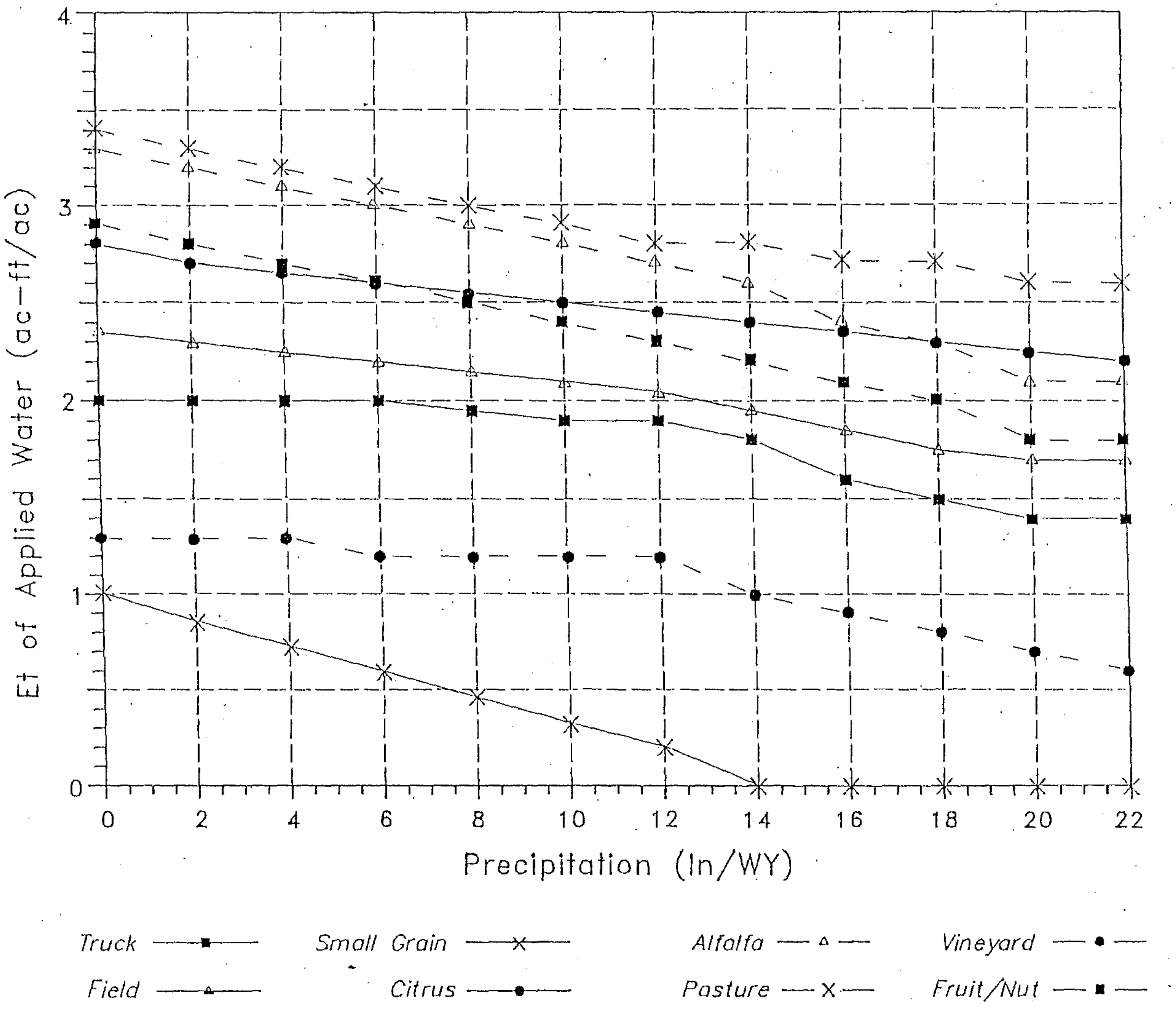

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Figure 4-9
Evapotranspiration of Applied Water by Crop
Santa Maria Valley Study Area

accommodate the variation from year to year in proportions of different crop types and in rainfall amounts. The annual pumpage estimates for the model area were then divided by the number of model cells simulating irrigation pumpage (e.g., those shown in Figures 4-6 and 4-7) to calculate an average per-cell pumpage amount. This areal averaging of the pumpage was done because the crop density and distribution precluded simulating pumpage from individual crop parcels; further, it was thought that the averaging would not cause any appreciable difference in simulated hydraulic head (compared to simulating pumpage from individual crop parcels) throughout the model area, given the generally even distribution of observed hydraulic head in the study area (e.g., a lack of localized pumping depressions) throughout the hydrologic period.

The irrigation pumpage to be simulated in the model was calculated by utilizing the estimates of annual pumpage detailed above in conjunction with the reported irrigation efficiencies for the area, which ranged from approximately 50 percent in the eastern-most portion of the study area to 90 percent in the Guadalupe area (due primarily to the distribution of soil types) (Worts, 1951). To accommodate the variable efficiencies, the model area was divided into three zones of different irrigation efficiencies: western area, 85%; central area, 75%; and eastern area, 65%. The per-cell estimates of annual pumpage were adjusted upward, based on these efficiencies; i.e., slightly higher in the eastern zone than in the western zone. The resulting estimate of irrigation pumpage accommodates the progressively lower irrigation efficiencies (and thus, greater irrigation pumpage per model cell) toward the eastern part of the study area.

The estimated irrigation pumpage was simulated using MODFLOW's well package; the pumpage was distributed throughout the model cells that corresponded to the historical areas of irrigation from model layers 2, 3, and 4 (corresponding to the upper 250 to 600 feet of the aquifer system). The irrigation pumpage simulated in the model and the associated acreage are presented in a hydrograph, which illustrates the gradual long-term increase in agriculture in the study area over the modeled period (Figure 4-10). These estimates are similar to previously-reported ones from a study conducted in a similar study area (Miller and Evenson, 1966); other studies have estimated the irrigation pumpage within larger study areas and are not comparable. The irrigation pumpage was simulated as

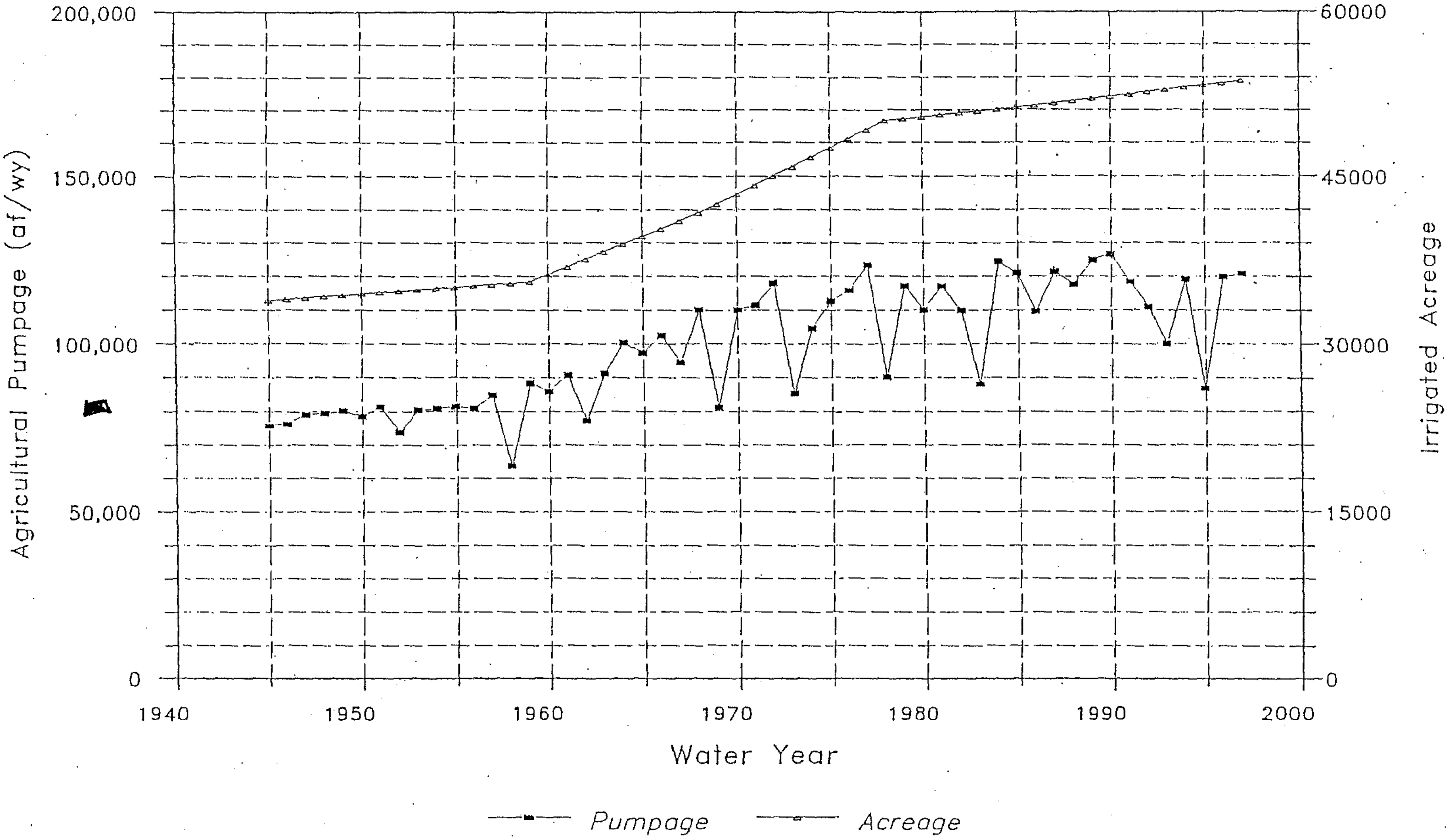

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Figure 4-10
Historical Irrigated Acreage and Agricultural Pumpage
Santa Maria Valley Study Area

outflow from the model's aquifer system, but only the crop requirement component of the pumpage (ET_{aw}) is simulated as being permanently removed from the system. The supplemental component of the pumpage for accommodating the irrigation efficiencies was assumed to return to the aquifer system in entirety and was simulated as recharge to the system (irrigation return flows), as described later in this subsection.

The municipal and industrial (M&I) pumpage simulated in the model included the municipal pumpage of the Cities of Santa Maria and Guadalupe, the Southern California Water Company (CalCities), and the Nipomo Community Services District (NCSD), and the industrial pumpage of the UnoCal-Guadalupe, Union Sugar, and PictSweet facilities. The municipal pumpage was based on historical records kept by the municipalities and the industrial pumpage was based on summary reports (Toups Corporation, 1976; Miller and Evenson, 1966) and available records in the files of the CCRWQCB. The locations of the municipal wells and industrial facilities included in the model are shown on a map of the study area (Figure 4-11) and the M&I pumpage simulated in the model is presented in a hydrograph, which shows a gradual long-term increase in pumpage over the modeled period (Figure 4-12). The M&I pumpage was simulated using MODFLOW's well package; the pumpage was distributed to the model cells corresponding to the known well and facility locations from model layers 2 through 5 (the upper 400 to 1,400 feet of the aquifer system). The municipal pumpage was distributed to the different layers based on each well's completion depths, and the industrial pumpage was distributed evenly between the layers (multiple wells were used at the facilities and completion depths were not available for all wells).

The recharge components simulated in the model are precipitation, irrigation return flows, treated municipal waste water applications to land , and processing water (industrial) applications. The amount of precipitation recharge was based on the results of a study conducted in Ventura County (specifically Oxnard, an area with conditions similar to the Santa Maria Valley) in which field determinations were made of the portion of rainfall that infiltrated below the root zone to the main ground-water body (Blaney, 1933). The results indicated that the amount of rainfall infiltrating the ground surface and percolating below the root zone varied, depending on the type of vegetative

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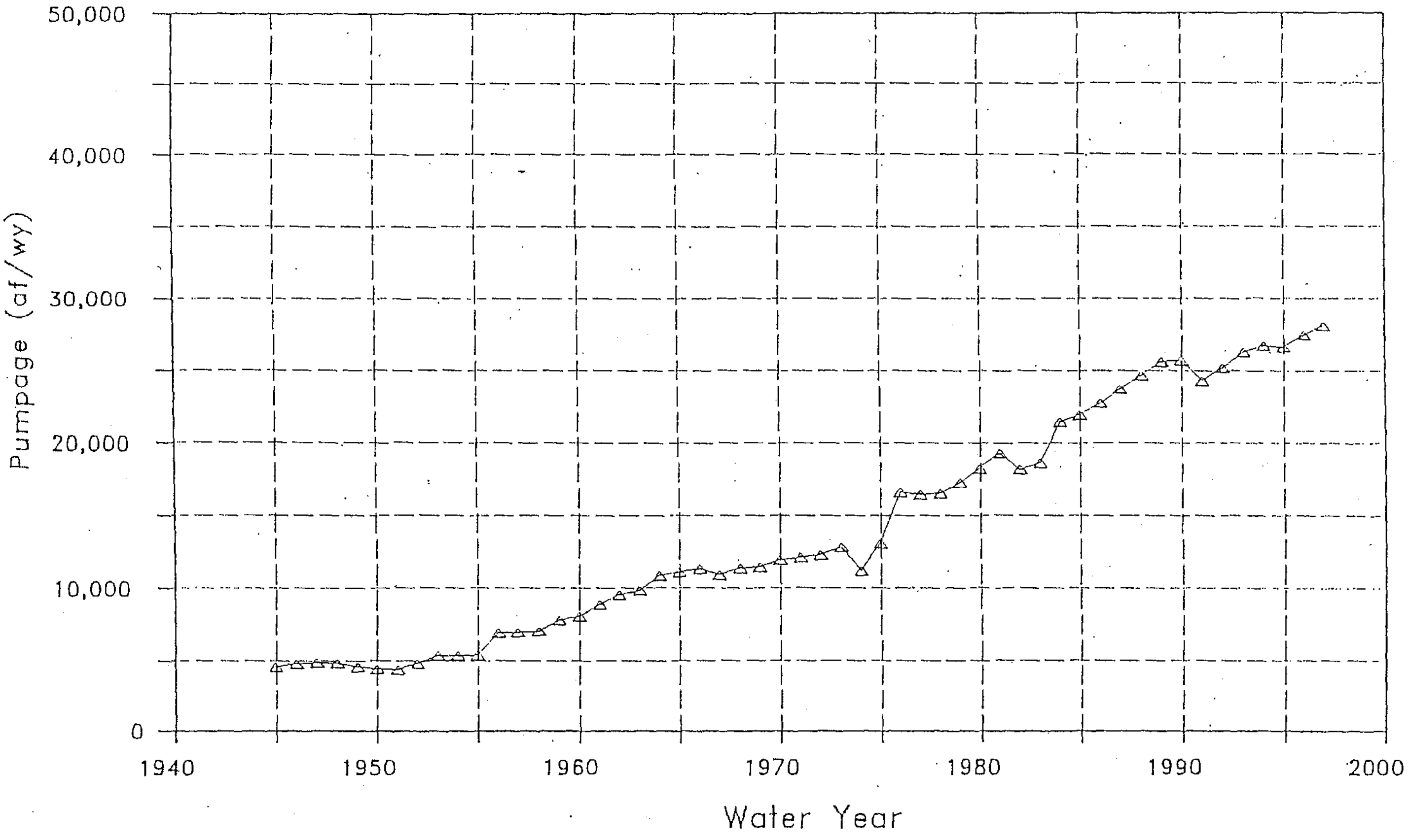

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Figure 4-12
Historical Municipal and Industrial Pumpage
Santa Maria Valley Study Area

ground cover present. In particular, the proportions of rainfall recharging the ground-water body were as follows: approximately 50 % of the rainfall in excess of 12 inches (within a year) in irrigated land; 80 % of the rainfall in excess of 15 inches in grassland; and 20 % of the rainfall in excess of 18 inches in brushland. In this case, the soil moisture (at the beginning of the rainy season) of irrigated land was higher than grassland, which was in turn higher than brushland; thus progressively more of the annual rainfall went to replenish the soil moisture before percolating beyond the root zone during the later part of the rainy season. In the study, non-irrigated cropland was considered to have soil moisture conditions similar to grassland areas.

During the determination of historical land use patterns in the study area (from crop survey maps) described earlier in this subsection, the areas of grassland, brushland, and non-irrigated crops were also defined throughout the model's historical period. Ground-water recharge from precipitation in the various areas was simulated using MODFLOW's recharge package, and the recharge was distributed throughout the model cells that corresponded to the various areas according to the recorded historical rainfall at the Santa Maria gauge and the rainfall proportions determined in the Ventura County (Oxnard) study. As a result, those model cells "overlying" the irrigated cropland areas only received recharge to the model during years when the rainfall exceeded 12 inches, and then only 50 % of the precipitation amount in excess over the 12 inches. Those model cells "overlying" the grassland and non-irrigated cropland areas only received recharge to the model during years when the rainfall exceeded 15 inches, and then only 80 % of the amount of precipitation over the 15 inches. Finally, those model cells "overlying" the brushland areas only received recharge to the model during years when the rainfall exceeded 18 inches, and then only 20 % of the amount of precipitation over the 18 inches. The proportion of rainfall infiltrating urban areas was not known, and the precipitation recharge for these areas was simulated as 15 % of the annual rainfall. All precipitation recharge simulated in the model was applied to the upper layer (layer 1) of the model. During calibration, none of these proportions (and thus the associated recharge) was adjusted.

As noted earlier in this subsection, all of the supplemental component of the estimated irrigation pumpage (to accommodate the irrigation efficiencies) was assumed to return to the aquifer system.

These irrigation return flows were simulated as recharge to the system using MODFLOW's recharge package; the recharge was distributed throughout the model cells that corresponded to the historical areas of irrigation and applied to layer 1 of the model.

Additional recharge to the basin from the localized application of treated municipal waste water and processing water was simulated in the model. This included treated waste water from the Cities of Santa Maria and Guadalupe, the Laguna Sanitation District, and the NCSD, and processing water (industrial) from the UnoCal-Guadalupe, Union Sugar, and PictSweet facilities (see Figure 4-11). The industrial pumpage (discharge) was estimated as described earlier in this subsection; the subsequent disposal of this water (by application to land), specifically the portion recharged to the aquifer system, is simulated in the model using MODFLOW's recharge package. The volume of treated waste water applied to land was compiled from CCRWQCB files and summary reports, and the portions recharged to the aquifer system are simulated in MODFLOW's recharge package. It was assumed that 60 to 70 % of the applied treated water was recharged to layer 1 of the system, depending on the method of application. The varying starting dates of operation for the facilities during the model's hydrologic period are accommodated by the model (e.g., operation of the NCSD facility, and therefore the simulated recharge in the model, did not begin until the mid-1980's). During calibration, none of these proportions (of the applied water) was adjusted.

Model Calibration

As described earlier in this section, model calibration involves the process of adjusting initially input parameters such as aquifer properties, stream properties, boundary heads, and source/sink terms within reasonable ranges to obtain an acceptable match between observed and model-simulated hydraulic heads (ground-water levels). During the calibration of this model, adjustments were made primarily to the hydraulic conductivity and streambed conductance values, as discussed above; modifications were also made to the specific yield and storativity values and the estimated heads in the constant head cells along the coast. The estimated heads in the general head cells (northern boundary) and the source/sink terms were not adjusted during model calibration.

The calibration period of the model matched the model's hydrologic period, the 53-year period between Fall 1944 and Spring 1997. This calibration period encompasses the most notable factors or variations in the historical development of the basin's ground-water resources (e.g., the increased pumpage of ground water and the enhanced recharge from the Twitchell project), as well as several alternating cycles of wet and dry hydrologic conditions. Also, ground-water level data were available from numerous wells throughout the study area, in particular throughout the Santa Maria Valley, during the entire period. Semi-annual data were often available throughout large portions of the calibration period from many of these wells.

Model calibration was conducted by comparing observed ground-water levels with model-simulated hydraulic head for 28 wells located throughout the model area; this was done by a combination of visual comparison and a statistical analysis of the observed and simulated levels. The locations of the 28 calibration wells, approximately 10 wells each for layers 1, 2, and 3, are shown on a map of the study area (Figure 4-13). During calibration of this model, emphasis was placed on matching the ground-water levels from wells in the portion of the model area with the greatest hydraulic stresses (the Santa Maria Valley and Sisquoc plain), while maintaining an acceptable distribution of heads throughout the entire model area. Calibration was considered complete when the model-simulated heads closely approximated the observed levels; hydrographs of the simulated and observed head for several wells illustrate the extent of model calibration (Figures 4-14 through 4-17). Hydrographs of simulated and historical water levels for all of the calibration wells are included in the Appendix.

The statistical evaluation of the model calibration involved analyzing the "residuals" (calculated differences) between the observed and simulated ground-water levels for each observed level, on a well by well basis. In general, the mean of the residuals (the average across all model stress periods) for each calibration well provides an indication of how closely the model-simulated heads correspond to the observed water levels (e.g., small residuals would indicate a high degree of calibration). The standard deviation of the residuals shows the amount of spread around the mean residual (e.g., small standard deviations indicate less variation around the mean value). In this model calibration, the average of the residual means of the 28 calibration wells was 5.5 feet with a standard deviation of 9.2

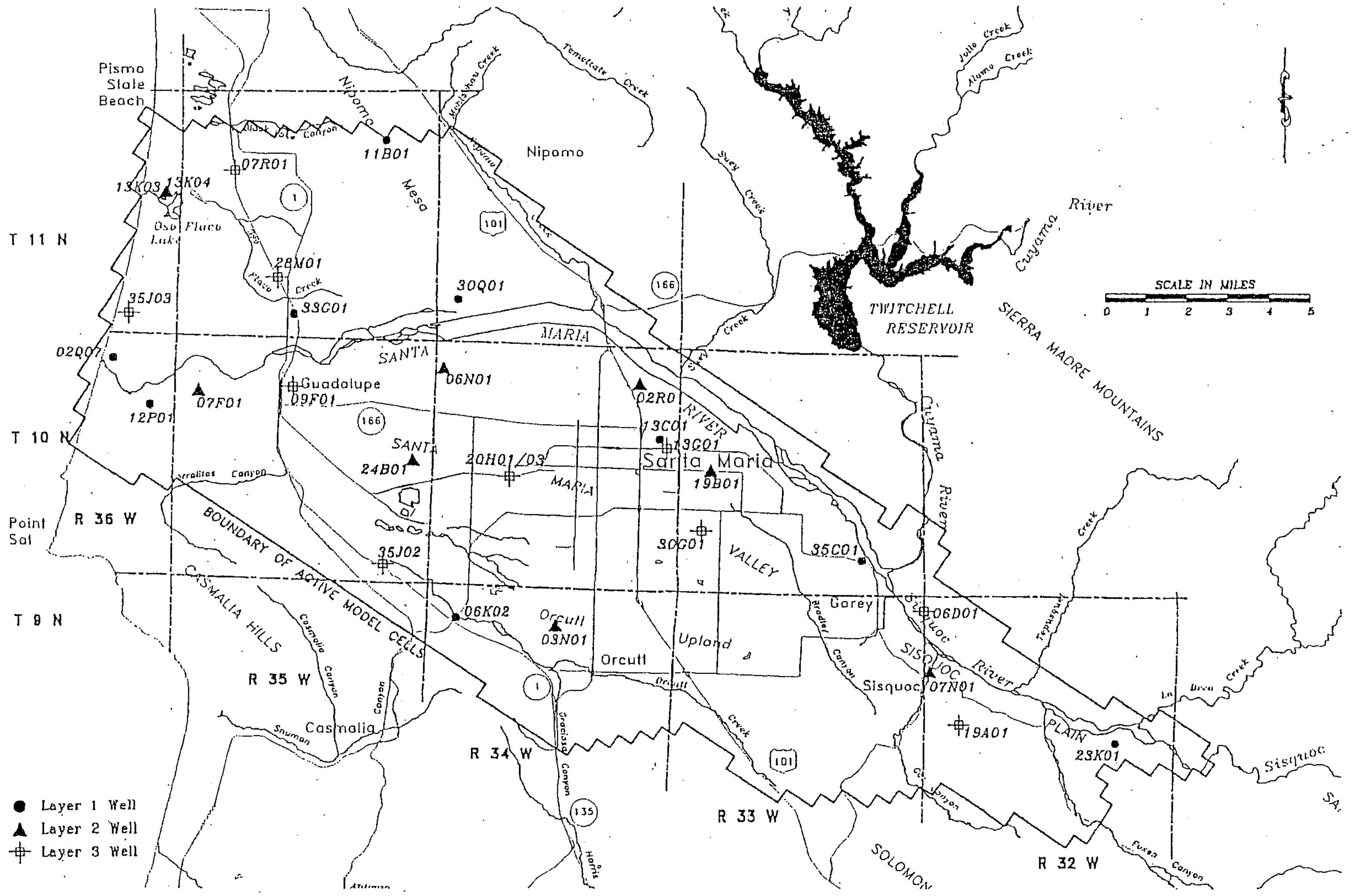

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Figure 4-13
Calibration Wells for Layers 1, 2, and 3
Santa Maria Ground-Water Model

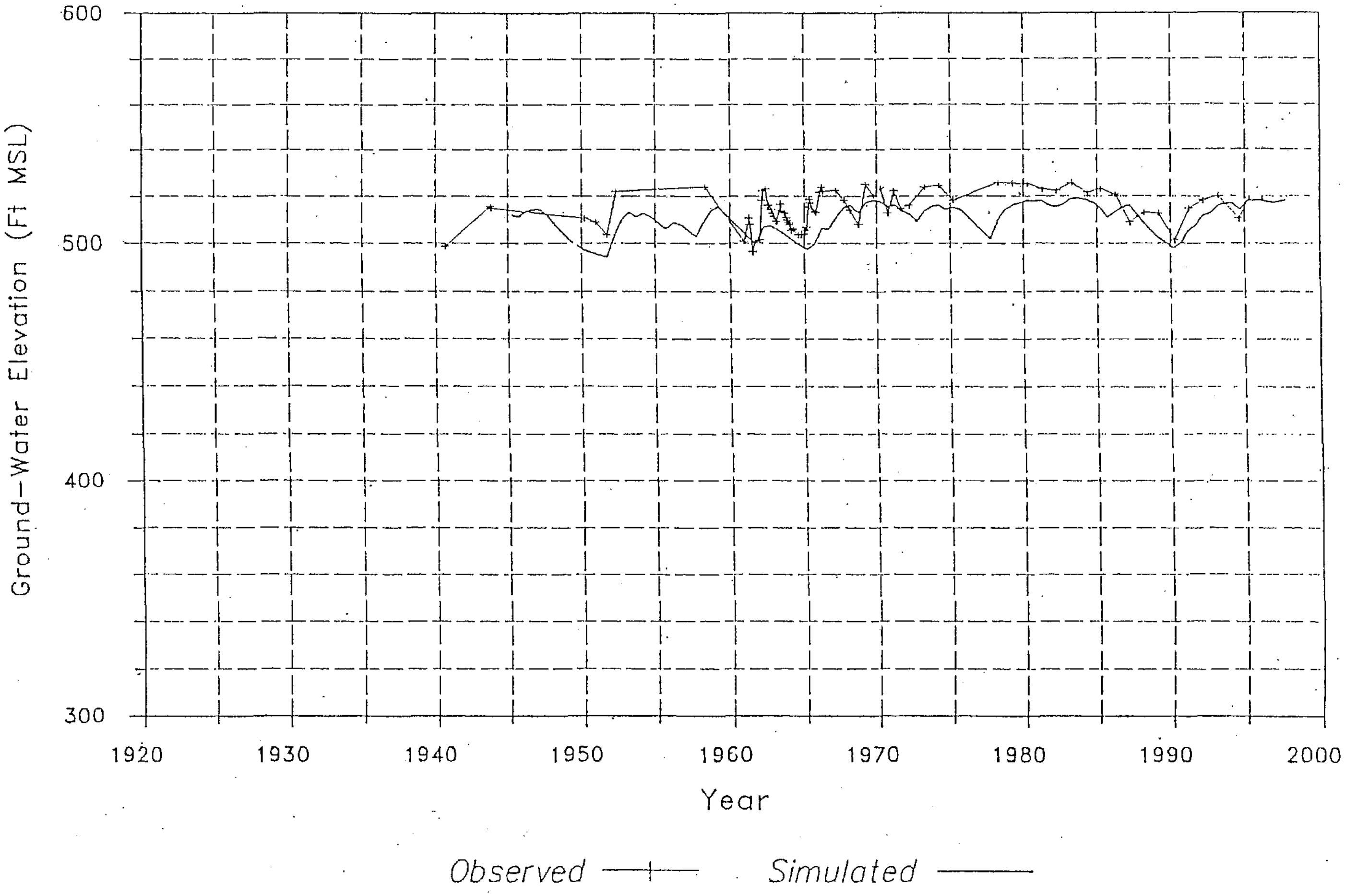

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Figure 4-14
Observed vs. Simulated Ground-Water Elevations
Well 9N/32W-23K1, Sisquoc Valley (Layer 1)
Santa Maria Ground-Water Model

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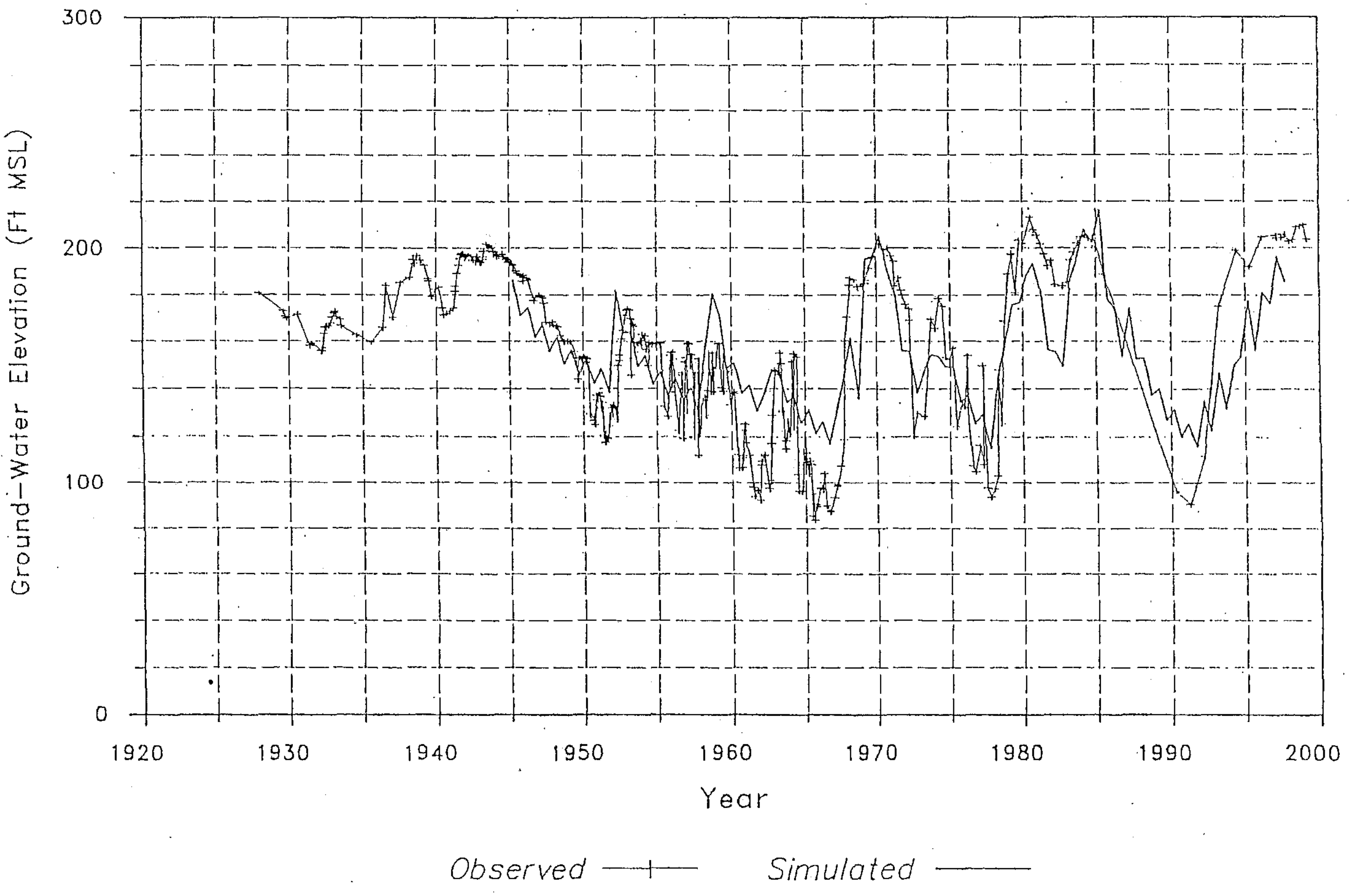

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Figure 4-15
Observed vs. Simulated Ground-Water Elevations
Well 10N/33W-19B1, East of Santa Maria (Layer 2)
Santa Maria Ground-Water Model

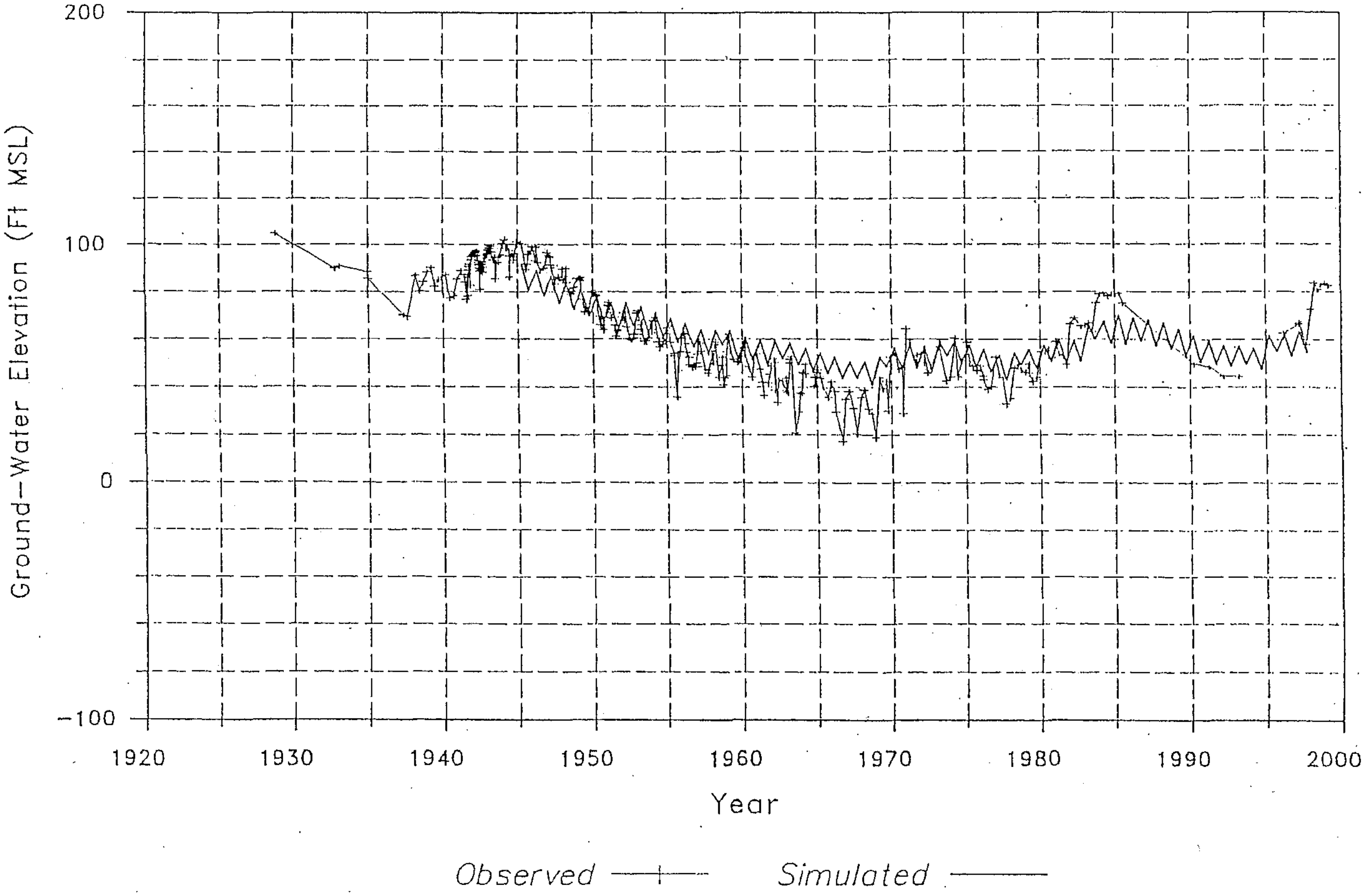

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Figure 4-16
Observed vs. Simulated Ground-Water Elevations
Well 10N/35W-24B1, Central Santa Maria Valley (Layer 2)
Santa Maria Ground-Water Model

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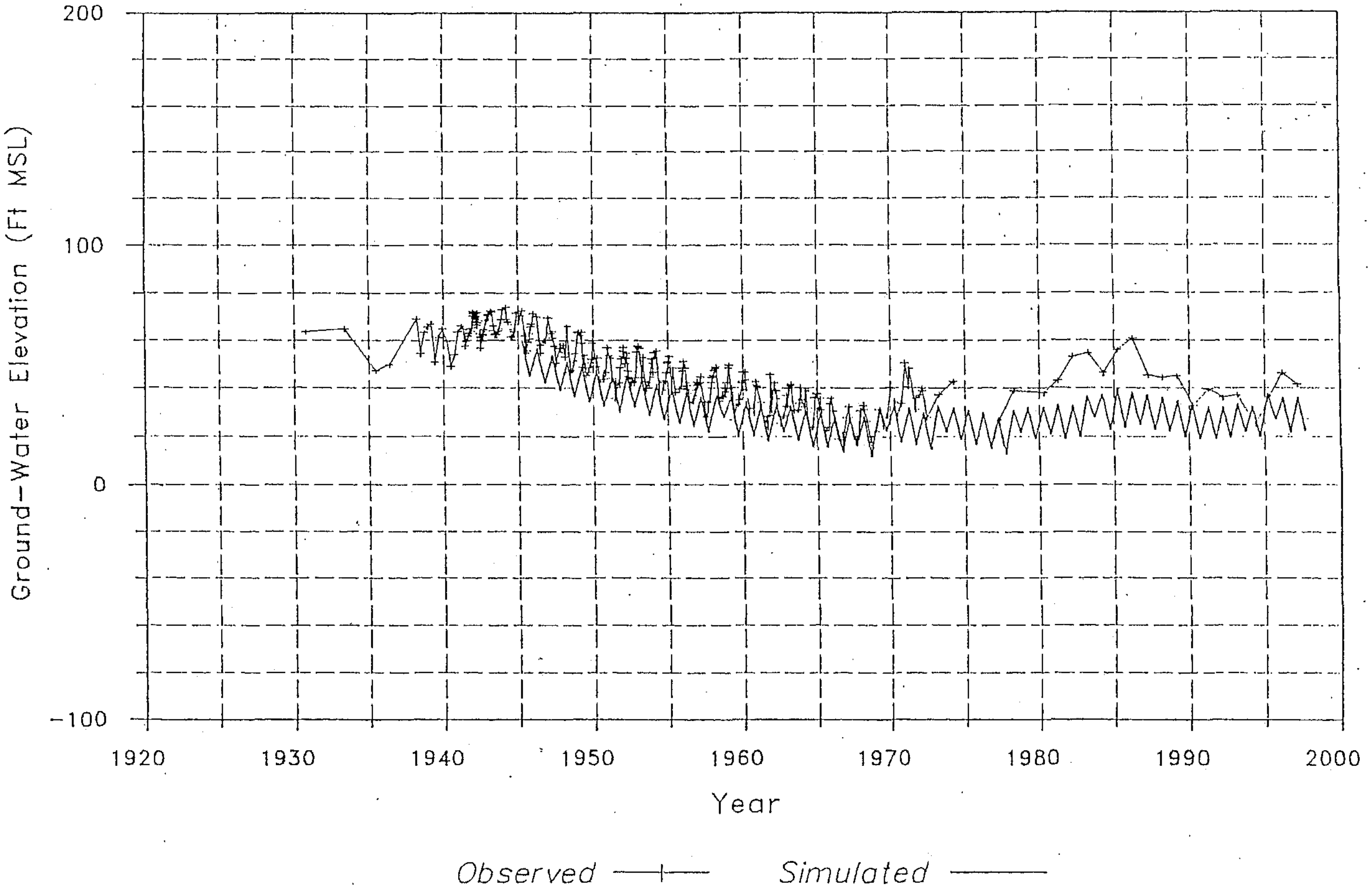

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Figure 4-17
Observed vs. Simulated Ground-Water Elevations
Well 10N/35W-09F1, Guadalupe Area (Layer 3)
Santa Maria Ground-Water Model

feet as shown in Table 4-2. This indicates that, on average, simulated ground-water levels are somewhat higher than observed levels in the calibration wells. As an additional evaluation of the model calibration, the absolute values of the residuals were also calculated; the mean and standard deviation of the absolute values were 13.2 and 7.2 feet, respectively, as shown in Table 4-2. This indicates the absolute magnitude of the difference between observed and simulated ground-water levels, on average, in the calibration wells. These residuals are considered acceptable given the large scale of the model, which encompasses the great majority of the Santa Maria ground-water basin (approximately 250 square miles), and the complexity of hydrogeologic conditions within the basin, which experiences large seasonal and year-to-year fluctuations in ground-water levels to varying extents throughout the basin (see Figure 3-9).

An additional component of the model calibration involved reviewing the simulated streamflows for the Santa Maria River (the "at Guadalupe" gauge). A hydrograph of the observed and simulated flows at this location (Figure 4-18) provides an indication that the model simulates the streamflow reasonably well throughout the calibration period and, thus, the associated stream interaction with the aquifer system (primarily recharge to the basin).

Sensitivity Analysis

A sensitivity analysis was conducted to measure the model's sensitivity to changes in the most significant input parameters. The analysis was conducted by adjusting the value of each input parameter within a specified range, and then comparing the resulting simulated heads with those from the calibrated model. Parameters included in the sensitivity analysis were horizontal hydraulic conductivity, leakance, streambed conductance, storativity, and specific yield. With the exception of hydraulic conductivity and streambed conductance, each of these parameters was adjusted upward and downward by an order of magnitude from the calibrated values. Hydraulic conductivity and streambed conductance were increased by 50 % and decreased by one-half (hydraulic conductivity) or a tenth (streambed conductance) from the calibrated values. The results of the sensitivity analysis were measured by comparing the difference between measured and simulated heads at the calibration

Table 4-2

Mean and Standard Deviation of Residuals and Absolute Values of Residuals for Calibration Wells

	Residuals		Absolute Values of Residuals	
Well Number	Mean (ft)	Standard Deviation (ft)	Mean (ft)	Standard Deviation (ft)
Layer 1 Wells				
09N/32W-23K1	-5.43	5.97	6.69	4.48
09N/34W-06K2	24.55	5.15	24.55	5.15
10N/33W-35C1	-15.23	19.38	19.89	14.41
10N/34W-13C1	31.94	13.98	31.94	13.98
10N/36W-02Q7	3.53	1.30	3.53	1.30
10N/36W-12P1	-5.94	1.57	6.02	1.47
11N/34W-30Q1	9.36	8.91	10.79	7.08
11N/35W-11B1	13.23	11.18	14.82	8.88
11N/35W-33G1	-1.50	6.99	5.60	4.40
11N/36W-13K3	2.56	0.77	2.56	0.77
Layer 2 Wells				
09N/32W-07N1	20.63	16.56	21.49	15.43
09N/34W-03N1	8.11	6.28	8.11	6.28
10N/33W-19B1	5.90	21.54	18.21	12.81
10N/34W-02R1	-1.16	9.40	6.72	6.62
10N/34W-06N1	7.54	8.60	9.91	5.66
10N/35W-07F1	-0.54	6.06	4.83	3.65
10N/35W-24B1	10.00	9.40	12.03	6.56
11N/36W-13K4	12.51	0.68	12.51	0.68
Layer 3 Wells				
09N/32W-06D1	-31.95	11.85	31.95	11.85
09N/32W-19A1	1.87	5.60	5.28	2.48
10N/33W-30G1	36.72	17.47	36.84	17.22
10N/34W-13G1	0.28	13.90	11.80	7.11
10N/34W-20H1/H3	15.65	11.48	16.84	9.56
10N/35W-09F1	-4.15	6.63	5.89	4.75
10N/35W-35J2	9.24	15.06	13.83	10.75
11N/35W-07R1	13.88	10.93	14.20	10.47
11N/35W-28M1	-8.75	8.15	9.61	7.02
11N/36W-35J3	1.38	2.71	2.52	1.60
Mean of Values, All Calibration Wells	5.51	9.20	13.18	7.23

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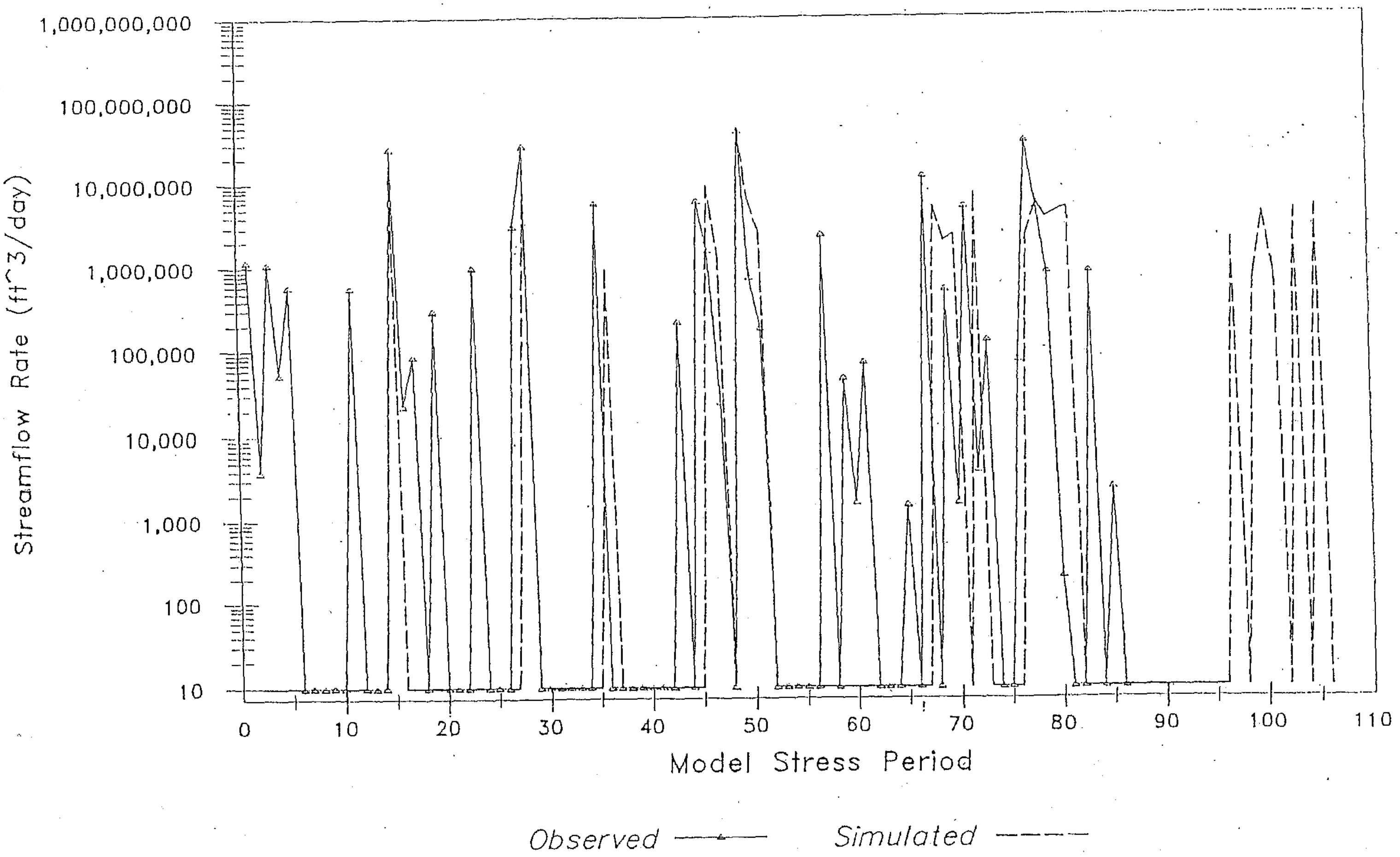

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Figure 4-18
Observed vs. Simulated Streamflow Rates
Santa Maria River at Guadalupe
Santa Maria Ground-Water Model

wells. The mean of the absolute values of the head residuals from the calibrated model was compared to those from the sensitivity analysis for each adjusted parameter as shown in Table 4-3.

The model was most sensitive to changes in specific yield, leakance, and streambed conductance. An order of magnitude decrease in specific yield (a substantial decrease from 15 to 1.5 %) caused the residual mean to increase by more than an order of magnitude (from approximately 13 to 240 feet); an order of magnitude increase doubled the calibrated model's residual mean. The response of the model to changes in leakance and streambed conductance, either increasing or decreasing them, was to generally double or triple the residual mean from the calibrated model. The sensitivity of the model to changes in hydraulic conductivity and storativity were found to be almost negligible, with a difference in the residual means of no more than 1.5 feet.

Water Budget

Calculation of a water budget was not the primary objective of the ground-water flow model, but an analysis of the summation of inflow and outflow components produced by the model provides a better understanding of the model and the ground-water flow system being simulated. The water budget calculated by the model is required to balance; i.e., the inflows must approximately equal outflows. The components of inflow to the model include: ground-water flow across the model boundary cells (constant head cells along the coast and general head cells along Black Lake Canyon); streamflow losses (Santa Maria, Cuyama, and Sisquoc Rivers and tributaries); river losses (Orcutt Creek); recharge (precipitation, irrigation return flow, and waste water applications); and inflow from storage. The components of outflow from the model include: ground-water flow across the model boundary cells (constant head cells and general head cells); streamflow gains (Santa Maria, Cuyama, and Sisquoc Rivers and tributaries); river gains (Orcutt Creek); pumpage (agricultural and M&I); and outflow to storage.

The water budget indicates that streamflow loss from the main stream system is the largest inflow component to the aquifer system, averaging approximately 72,000 acre-feet/year (afy) during the

Table 4-3

Sensitivity Analysis of Parameters Used In Calibrated Model

Parameter	Adjustment Factor	Calibrated Model		Sensitivity Analysis	
		Absolute Value Residual Mean (ft)	Standard Deviation (ft)	Absolute Value Residual Mean (ft)	Standard Deviation (ft)
Hydraulic Conductivity	0.5	13.18	7.23	14.39	7.31
	1.5	13.18	7.23	14.61	7.76
Leakance	0.1	13.18	7.23	29.13	12.23
	10	13.18	7.23	50.05	14.65
Streambed Conductance	0.1	13.18	7.23	36.66	15.29
	1.5	13.18	7.23	12.58	7.33
Storativity	0.1	13.18	7.23	12.16	7.07
	10	13.18	7.23	12.21	7.06
Specific Yield	0.1	13.18	7.23	239.35	37.61
	10	13.18	7.23	21.57	10.29

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entire 53-year model hydrologic period. The outflow from the aquifer to the stream system is quite small (an average of 400 afy), occurring in only limited areas of the model area near Guadalupe, so the average net inflow to the aquifer system from streamflow is approximately 71,600 afy. The second largest inflow component is recharge from precipitation, irrigation return flow, and waste water application, averaging approximately 42,000 afy. The recharge component is a "fixed" inflow (not dependant on model simulated heads) and thus there is no recharge outflow from the model. A hydrograph of the net stream inflow and recharge to the model over the hydrologic period illustrates the long-term fluctuation about their respective averages and the relation between these two inflow components; i.e., increased stream inflow with wetter hydrologic conditions (Figure 4-19). A minor inflow component is the river losses from Orcutt Creek to the aquifer, with an average net inflow of approximately 3,500 afy.

The largest component of outflow from the aquifer system is pumpage for agricultural and M&I uses, averaging approximately 115,000 (afy) during the model hydrologic period. The pumpage component is a fixed outflow from the model based on the estimates of historical agricultural pumpage and the historical records of M&I pumpage (see Figures 4-10 and 4-12). The remaining components of model inflow and outflow are across model boundaries, and the largest of these is the ground-water flow out of the model across the constant head cells along the coast (averaging approximately 25,000 afy). Hydrographs of the net inflow and outflow rates for each component, which illustrate their long-term fluctuations and relative magnitudes, are included in the Appendix.

The change in aquifer storage associated with the fluctuation of the inflow and outflow components described above is calculated by the model as part of the water budget. A hydrograph of the annual net storage change during the model hydrologic period illustrates the repeated fluctuation between conditions of aquifer storage loss and gain within the basin during the last approximately 50 years (Figure 4-20). The net storage change was negative during dry years when more ground water was flowing out of aquifer storage than was flowing in (resulting in declining ground-water levels). Positive net storage changes occurred during wet years when aquifer storage was increasing (producing rising ground-water levels). A comparison of the storage change and stream

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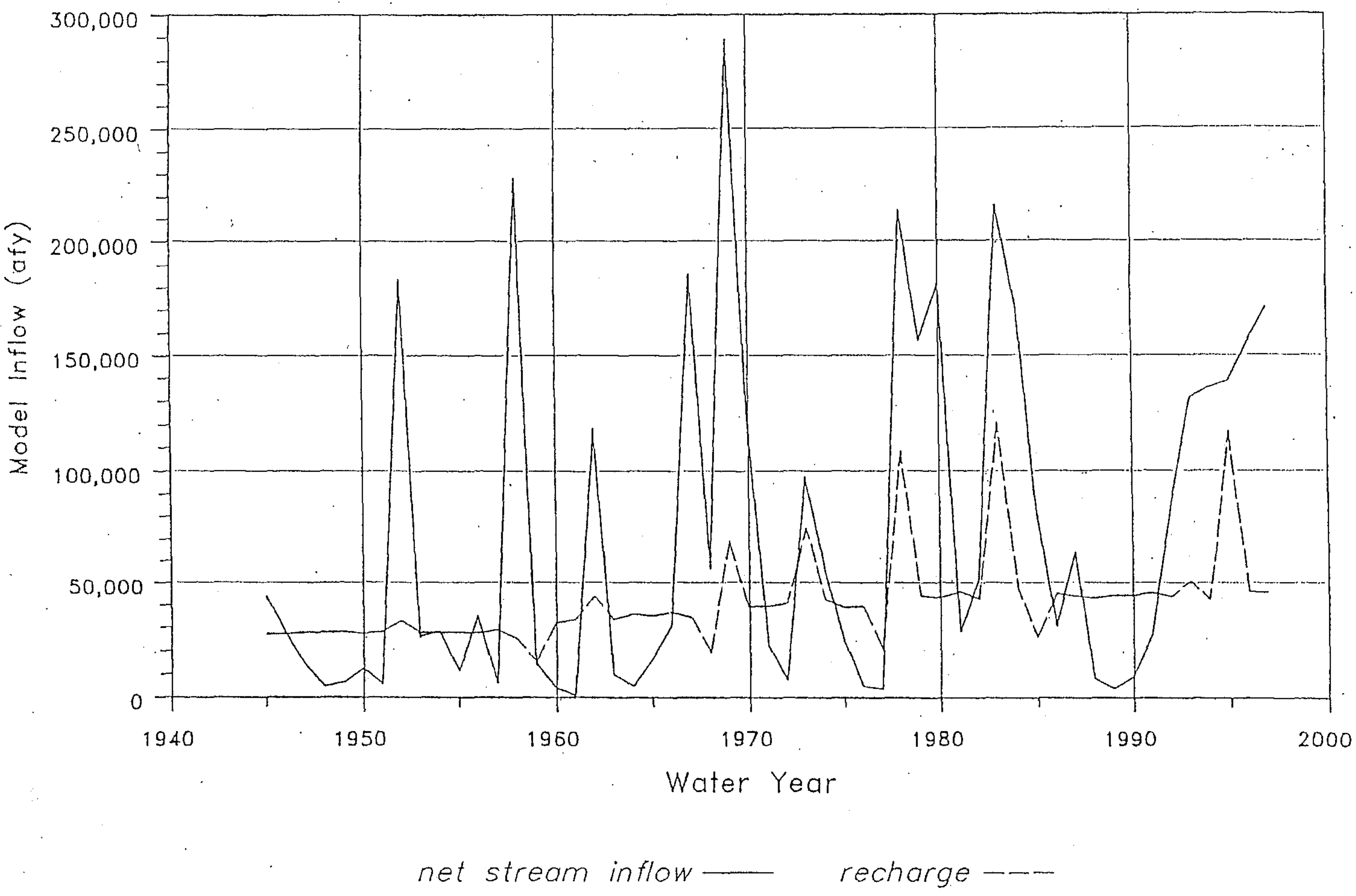

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Figure 4-19
Model Inflow from Streams and Recharge
Santa Maria Ground-Water Model

Simulation of Historical Conditions

As mentioned above, the calibrated model simulates the historical ground-water flow and levels within the basin for the period from 1944 to 1997. The extent of model calibration was described in the **Ground-Water Flow Model** section and demonstrated with several hydrographs comparing observed and model-simulated water levels in individual calibration wells. In addition, the model calibration results were evaluated by statistical analysis of the residual heads (calculated difference between observed and simulated levels) in the calibration wells. The water budget also provided an indication that the model simulates historical conditions reasonably well; it responds appropriately to variations in climatic conditions during the calibration period, and the relative inflow and outflow values calculated for each component are considered reasonable for the ground-water conditions existing in the model area.

The simulation of historical conditions may be seen on a basin-wide basis in contour maps of simulated ground-water elevation for different periods of time during the model hydrologic period. Two periods were selected for this purpose and the contour maps are presented herein: 1968, at the approximate mid-point of the hydrologic period and a time when ground-water levels within the study area had reached historical low levels (Figure 5-1), and 1997, at the end of the hydrologic period and a recent time when water levels had recovered to near historical-high levels (Figure 5-2). The simulated contours shown are for layer 3 of the model, which corresponds to the uppermost portion of the Paso Robles Fm. (the contours for layers 1 and 2 are similar but contain unsaturated areas to varying extents in the Orcutt to Cat Canyon area, as has been observed in that portion of the Orcutt Fm.). The contour maps of simulated levels closely match the corresponding contour maps of observed levels in 1968 and 1997 (see Figures 3-11 and 3-12) in the overall flow directions and pattern, including the areas of stream recharge along the Santa Maria River and the areas of the majority of municipal pumpage near Orcutt. Simulated ground-water levels in the Nipomo Mesa and along the coast also match the observed levels; however, this is primarily due to the model's boundary cells (general head cells along Black Lake Canyon and constant head cells along the coast).

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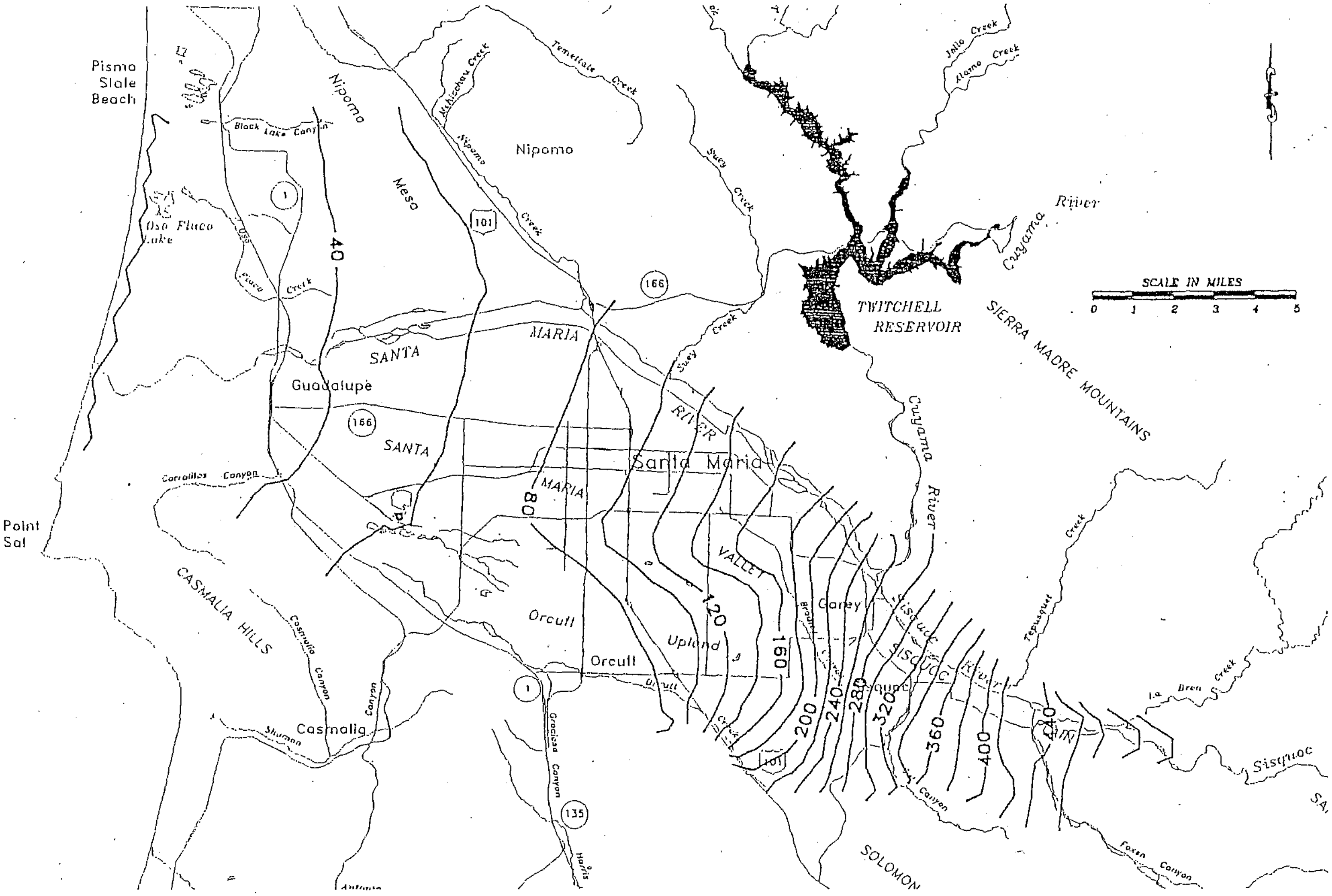

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Figure 5-1
Contours of Simulated Ground-Water Elevation, Spring 1967
Santa Maria Valley Study Area

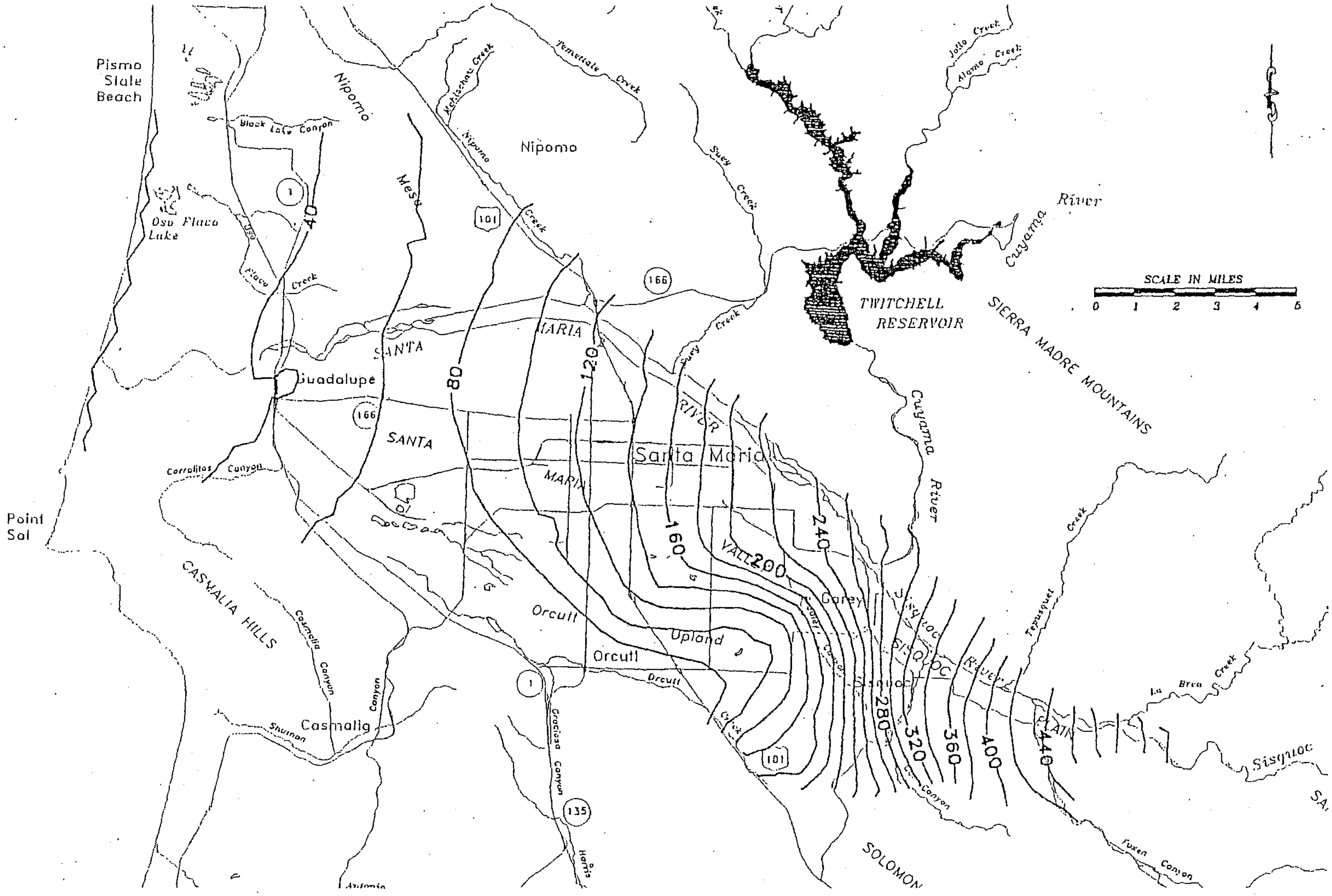

Figure 5-2
Contours of Simulated Ground-Water Elevation, Spring 1997
Santa Maria Valley Study Area

Potential Model Applications

As introduced above, the model can be used to assess the likely state of ground-water basin conditions (ground-water levels and storage, including trends, and ground-water flow) under a variety of revised historical or alternative future conditions. For example, based on general interests expressed in recent years, various scenarios might be drafted to individually or collectively examine the benefits of Twitchell Reservoir, the benefits of importing supplemental (State Water Project) water for municipal supply, and the impacts of future changes in agricultural and/or municipal land and water use. For general consideration in the future, the following scenarios have been developed to illustrate potential applications of the model in the overall planning and management of water resources in the basin. The four scenarios discussed below are summarized in Table 5-1.

Base Cases

The base case can be essentially an examination of the overall historical period of record to assess the status of the basin under those historical conditions. In this case, given the lengthy hydrologic and concurrent calibration period, 1944-97, the base case would be a numerical simulation that would express ground-water level response to historical hydrology, and to historical land and water use as well as water management actions (e.g., the addition of Twitchell Reservoir, beginning about midway through the modeled period); once calibrated as described herein, the base case would effectively reproduce actual historical ground-water level histories throughout the basin.

An "alternate" base case could be an extraction of a selected study period from the overall historical period of record to examine basin conditions through that study period. For purposes of this report, this latter alternate base case is used in the analysis of perennial yield and whether the basin is in overdraft, discussed in detail below.

Table 5-1

Possible Model Scenarios
Santa Maria Ground-Water Basin Management

Base Cases

Historical Conditions, 1944-1997
Selected Study Period, 1968-1989

No Project Alternative (i.e. no Twitchell)

Historical Hydrology, 1944-1997
Historical Land and Water Use, 1944-1997

Future M&I Alternative (with Twitchell)

Historical Hydrology (selected 22 year period)
Projected M&I Demand (through 2020)
- full State Water Project deliveries
- other (average "actual" deliveries)
- no State Water Project deliveries

Constant Agricultural Land and Water Use (1995)

Future Agricultural Alternative (with Twitchell)

Historical Hydrology (selected 22 year period)
Projected M&I Demand (through 2020)
- average "actual" State Water Project deliveries

Increased Agricultural Land Use and Pumpage

No Project Alternative

Recent analyses by the District, prior to the development of the ground-water model described herein, have concluded that the Twitchell project's augmentation of in-stream ground-water recharge has had a significant beneficial impact on the ground-water basin. Both the quantity (water levels and storage) and quality of ground water in the basin have benefitted from recharge attributable to Twitchell reservoir operations. In order for various interests in the Valley to understand the beneficial impact of the project over the last 30 years, and to also understand the need to maintain reservoir operations as a key component of water resource management in the Valley, the ground-water model could be used to analyze a so-called No-Project Alternative. In effect, in a No-Project Alternative, the Twitchell Dam and Reservoir could be "removed" from the system; stream recharge would be limited to the rainfall-runoff season; runoff in excess of the stream infiltration capacity would be lost to the ocean; and there would be no ability to store surface water for delayed beneficial release (i.e., for recharge) in a dry period (to extend stream recharge into a drought period). The No-Project Alternative could be simulated (modeled) over any selected hydrologic conditions (e.g., a theoretical repeat of actual historical conditions such as the 1944-97 model calibration period, or, alternatively, some other selected hydrologic period). The simulation(s) could also include one or more configurations of land and water use in the Valley (e.g., current conditions, or a repeat of historical buildup, or other).

For true No-Project comparison to what has actually transpired in the Valley, the longer term 1944-97 base case above (which includes the addition of Twitchell, as actually occurred, in the 1960's) could be compared to a simulated scenario with all the same hydrology, and with the same land and water use as occurred over that period, but without the addition of Twitchell Reservoir to capture runoff and regulate its release for in-stream recharge. The resultant, simulated ground-water levels and storage could then be compared to what has actually occurred to identify the differences, in terms of both magnitude and location, around the Valley.

recharge via, as was briefly discussed in the last couple of years, reclamation of some surface mining excavations along the Sisquoc River to in-channel and/or off-channel spreading basins. While the opportunities are not necessarily limitless, the ground-water model can be widely utilized to assess the probable impacts, whether beneficial or negative, of a range of future ground-water management activities in the basin.

Basin Yield and Balance

As introduced above, one of several potential applications for the ground-water flow model can be to examine ground-water level (and storage) responses in the basin over selected historical periods. One such period could be the entire period of record, while another could be some selected period of interest within the overall period of record. Either of them could be called a "base case", whether for examination of how the basin reacted to certain historical conditions or for establishment of some baseline against which to compare one or more simulations of future alternative scenarios in the basin. While the model might be used to examine such future scenarios as those described above, the main focus of the District in commissioning the development of the model was to assess whether pumping in the basin was within its perennial (or "safe") yield or, if not, whether it was in overdraft and by how much.

There are several possible definitions of the term perennial yield as it pertains to a ground-water basin. The most common definition of perennial yield, adopted for purposes of this report and discussion, is that amount of ground water that can be pumped from a basin on a sustained basis without an undesirable result. Common "undesirable results" of ground-water development in excess of perennial yield (i.e., "overdraft") include one or more of: long-term ground-water level decline (and associated decline in ground-water storage); ground-water quality degradation, including but not limited to sea water intrusion; and subsidence of the land surface, with attenuant impacts on buildings, other structures, surface drainage, etc.

In the Santa Maria Valley ground-water basin, most of the typical "undesirable results" have either not occurred or are of no reported concern. For example, there has been no detection of coastal or other ground-water quality change that might be considered indicative of sea water intrusion. In the subsidence arena, despite several significant short-term fluctuations of ground-water levels in certain parts of the basin as illustrated and discussed above, there has been no expressed concern about those fluctuations contributing to land surface subsidence. As a result, there is no established monitoring of land subsidence in the basin. In light of the absence of those "undesirable results" in the Santa Maria Valley, the focus of the perennial yield assessment using the ground-water model has been on ground-water levels and storage.

In a number of developed ground-water basins in California, notably including the Santa Maria Valley, it is possible to observe historical conditions, depending on the selection of a period for study, that might be interpreted as indicative of overdraft (notable and progressive ground-water level decline, at least for some period of time) or, conversely, indicative of surplus (notable ground-water level increases). The Santa Maria Valley is a particularly good illustration of various ground-water basin conditions when looking at one or more historical periods within the overall modeled period of record. For example, with the expansion of irrigated agriculture after World War II, particularly for truck cropping, there were progressive increases in irrigated acreage and ground-water pumpage for most of a 30 year period to about 1980. Corresponding with those pumping increases were notable ground-water level declines in much of the inland part of the Valley, at least through the late 1960's. In addition to pumping as a contributor to ground-water level declines, precipitation was generally dry over much of the 30 year period from the mid-1940's through the mid-1970's. On the other hand, a slower rate of agricultural land development and generally more constant (rather than increasing) pumpage since the late 1970's, complemented by a period of wet years from the mid-1970's through the early 1980's, resulted in notable ground-water level recoveries (to levels near those which preceded the post-World War II development). Somewhat complicating (beneficially) the overall ground-water basin picture is the introduction of Twitchell Dam and Reservoir, which was built to conserve runoff and regulate its release for in-stream ground-water recharge. Releases from Twitchell began to contribute to ground-water recharge in the late 1960's.

The net result of all the above is that it is possible to essentially "pick a study period - pick an apparent result". In other words, the status of the ground-water basin in terms of perennial yield and overdraft analysis is very much a function of what study period is selected. Selection of a study period from the late 1940's through the 1970's would likely lead to a conclusion that the basin was in overdraft; whereas, selection of a more recent study period from the late 1970's into the early 1980's could lead to a conclusion that there was surplus water in the basin.

In order to eliminate the bias that could result from inappropriate selection of a study period, and to report on the current state of the basin, a study period was selected on the basis of the following several criteria: long-term mean water supply; minimum change of ground-water storage in the unsaturated zone; inclusion of both wet and dry stress periods; adequate data availability; and near-present end of study period.

The long-term mean water supply criteria is a measure of whether the basin has experienced average natural ground-water recharge over a selected time period. Since precipitation is a measure of natural ground-water recharge, and since precipitation data are available for a long period of time, interpretation of precipitation data was used as a basis for selection of a study period. The long-term (1932-97) average annual precipitation at the Santa Maria gauge is 13.4 inches. Notable on the cumulative departure curve from mean annual precipitation (see Figure 3-16) are the wet conditions of the mid-1930's through the mid 1940's, followed by the long-term relatively dry period from the mid-1940's into the 1970's, followed by alternating wet (through the early 1980's, dry (through 1989), and wet (through the mid-1990's) periods. Since a study period should include essentially mean, or average, precipitation over its duration, it should have about the same cumulative departure from mean at the beginning and end of the study period. Pending consideration of other criteria, as follows, two study periods were initially selected: 1968-1989, and 1969-1995. Both periods fulfill the long-term mean water supply criteria based on precipitation.

The study period criteria to **minimize the change of ground-water storage in the unsaturated zone** is intended to recognize that the unsaturated zone above the ground-water surface can contain a varying but substantial amount of water at any give time, depending on immediately preceding hydrologic conditions. Regardless of the amount, the volume of ground water in storage in the unsaturated zone is essentially impossible to quantify with readily available data. Therefore, it can be removed as a factor in assessing conditions over a selected study period by purposely selecting the study period to start and end after dry years, thus effectively assuming that the unsaturated zone has "drained" to an equivalent storage volume at both the start and the end of the period. Of the two initially selected study periods noted above, one (1968-89) satisfies this criteria, while the other (1969-95) is exactly opposite; the beginning and end of the latter study period are both preceded by one or more wet years. Consequently, the selection of a study period for perennial yield evaluation was narrowed from the two initially selected periods to the 1968-1989 period.

Both initially selected study periods include both **wet and dry years** and/or periods of years. The inclusion of both types of years is important in assessing basin response to varying amounts of natural recharge, as well as response to yearly fluctuations in pumpage that are directly related to the amounts of precipitation in various years.

Data availability, as discussed in detail regarding overall ground-water model development for the entire period of record, is equally sufficient in both initially selected study periods.

The last of the study period criteria is that it **end near the present time.** By doing so, the study period can be used to assess ground-water conditions as they generally exist, rather than as they might have been in some earlier time period. Ideally, then, a study period for assessment of basin yield (and whether development is within perennial yield or in overdraft) would end in the mid-to late-1990's. Selection of an end-of-study period in that time would, however, violate the preceding criteria that would impose dry periods immediately before the beginning and end of the study period. In that light, the 22 year period from 1968 to 1989 better satisfies all the criteria for study period selection and is a more properly selected base period for evaluation of basin yield and overdraft (or lack thereof).

A final note on study period selection is that one could have been selected to begin earlier in time. Such a selection would have necessitated ending the study period earlier as well, in order to satisfy the antecedent dry period requirement for both ends of the period, thus moving it farther from the present. Perhaps more importantly, moving the start of the study period farther back in time would have practically introduced a large variable into the period in that the early years would have preceded Twitchell Reservoir while the balance of the study period would have included Twitchell. Ultimately, the base study period was chosen to begin in 1968 in order to accommodate all the criteria discussed above, but it was also chosen to consistently include the operation of Twitchell as a major ground-water management component in the overall system throughout the period.

The base period selected for analysis of current basin conditions, 1968-1989, is illustrated in Figure 5-3 and denoted as "dry to dry" to acknowledge the antecedent dry years prior to the beginning and end of the period. The more recent study period which was initially considered for comparison purposes, 1969-1995, is also illustrated on Figure 5-3 and is denoted as "wet to wet" to acknowledge the antecedent wet years prior to its end points.

Examination of ground-water level hydrographs, independent of model output, has previously shown that, on a long-term basis, there are no ongoing ground-water level declines that could be considered undesirable and indicative of overdraft. While there have been several short-term historical water level declines, in dry periods, each has been followed by a subsequent water level recovery during a wet period in which the ground-water basin has refilled, for all practical purposes to nearly full conditions; i.e., to near the same highest levels historically experienced in the basin prior to the increase in development since the mid-to late-1940's.

With the addition of the ground-water flow model described in this report, it is now possible to more closely examine the response of the basin to pumping distribution and other stresses over a study period appropriately selected, as described above, to assess the yield of the basin and whether pumping is within that yield. With recognition of the apparent basin conditions based on ground-water levels as described above, the results of which should obviously be consistent with a modeled

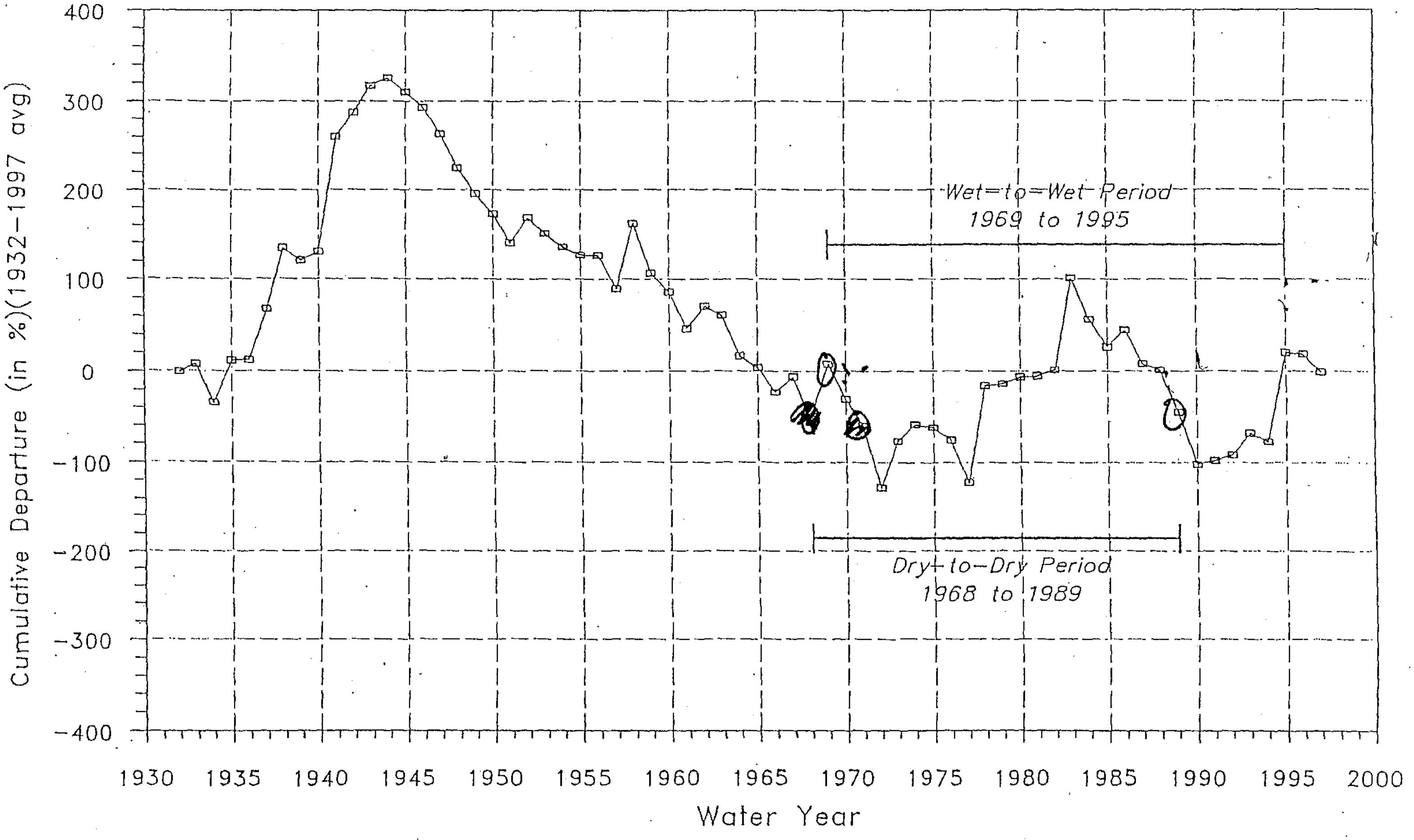

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Figure 5-3
Cumulative Departure Curve, Historical Precipitation
Dry-to-Dry and Wet-to-Wet Study Periods
Santa Maria Valley Study Area

simulation, the model was used to determine the yield of the basin and whether it is in overdraft. For the selected period described above, 1968-1989, which satisfies the necessary criteria for average natural recharge, no unbalanced storage in the unsaturated zone, inclusion of varying stress periods (wet and dry periods), and reasonable proximity to the present, the model-generated water budget shows no net change in storage. The variations in hydrologic conditions as well as fluctuations in pumpage over the 22 year period cause ground-water storage to fluctuate (somewhat dramatically as suggested by the observed historical fluctuations in ground-water levels), as illustrated by a hydrograph of cumulative change in aquifer storage (Figure 5-4). While a substantial amount of ground-water storage may intermittently be used to sustain water supply during periods of reduced recharge in dry years, the selected study period analysis shows that, for a reasonably long-term period that contains average recharge when considered over the entire period, there is no perennial deficit or decline in ground-water levels and storage. Thus, it can be concluded that the basin is developed to essentially its perennial yield and is in balance and not in overdraft.

For the study period selected in accordance with the criteria described above in order to assess basin yield and whether development is within that yield, average annual pumpage for all beneficial uses (agricultural plus municipal and industrial) in the basin was 124,000 acre-feet. While such a total annual pumping quantity is a useful reference in ongoing management of the basin, it should be noted that such numbers commonly and easily become fixed "monuments" against which future pumping volumes are inclined to be compared. Such "monument" status for average pumping over the perennial yield study period is inappropriate. Rather, such as an average pumping volume becomes a quoted "perennial yield" number, it should be qualified by noting that the basin is in balance at that rate of average pumping with three important provisions: 1) that the balanced basin conditions (no overdraft) are predicated on the continued distribution of pumpage, land use, and return flows as are currently prevalent; stated otherwise, perennial yield is in part influenced by the widespread distribution of pumping and recharge in the basin, and a substantive change in that distribution could change perennial yield; 2) that historical operation of the Twitchell reservoir for water conservation and augmented in-stream recharge is a key component of the perennial yield quantity; any substantial change in Twitchell conservation and recharge operations would impact the perennial yield of the

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Figure 5-4
Cumulative Aquifer Storage Change
Dry-to-Dry Study Period, 1968-1989
Santa Maria Ground-Water Model

basin; and 3) that average overall inflow to the system, as indicted by precipitation, remains consistent with the long-term average; obviously, any notable change in the average recharge to the overall system, as indicted by precipitation, would impact the perennial yield of the ground-water basin.

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Santa Maria Valley

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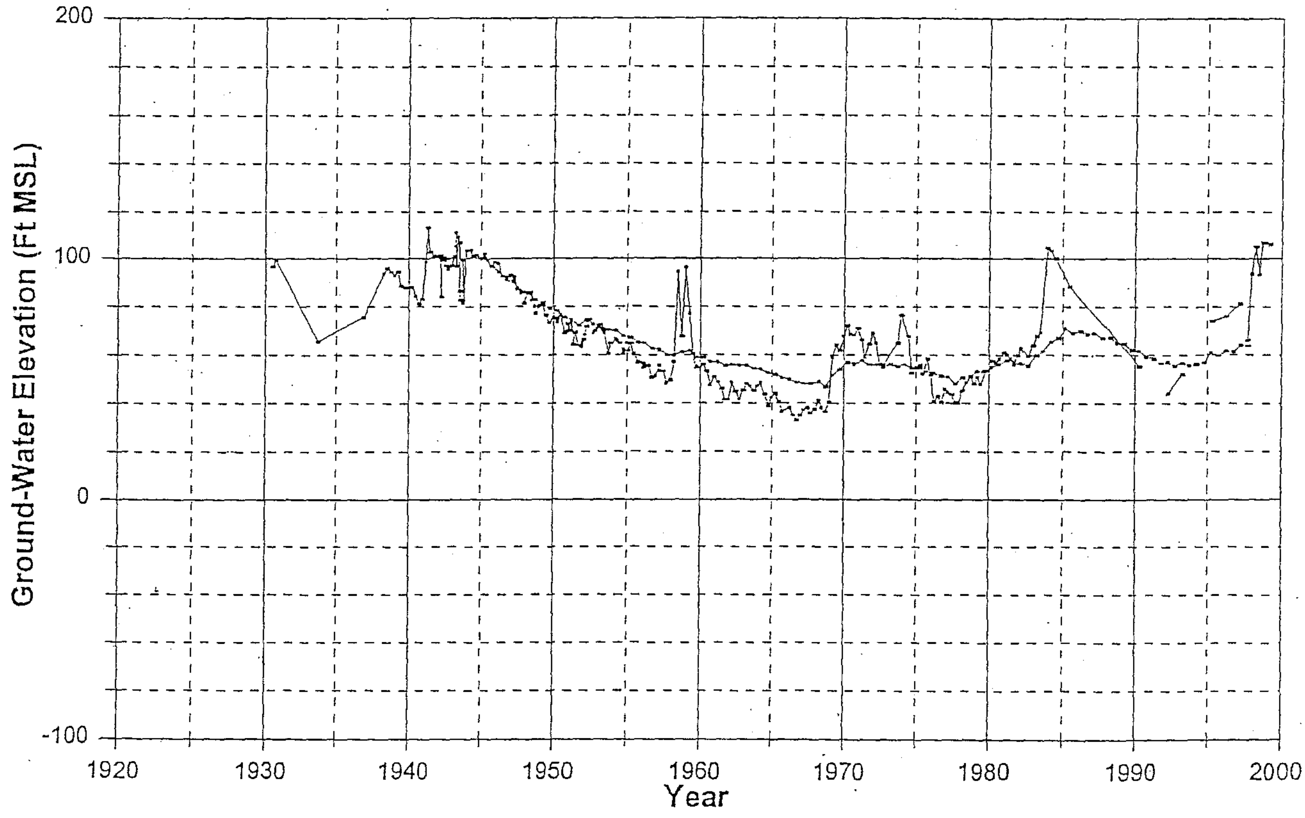

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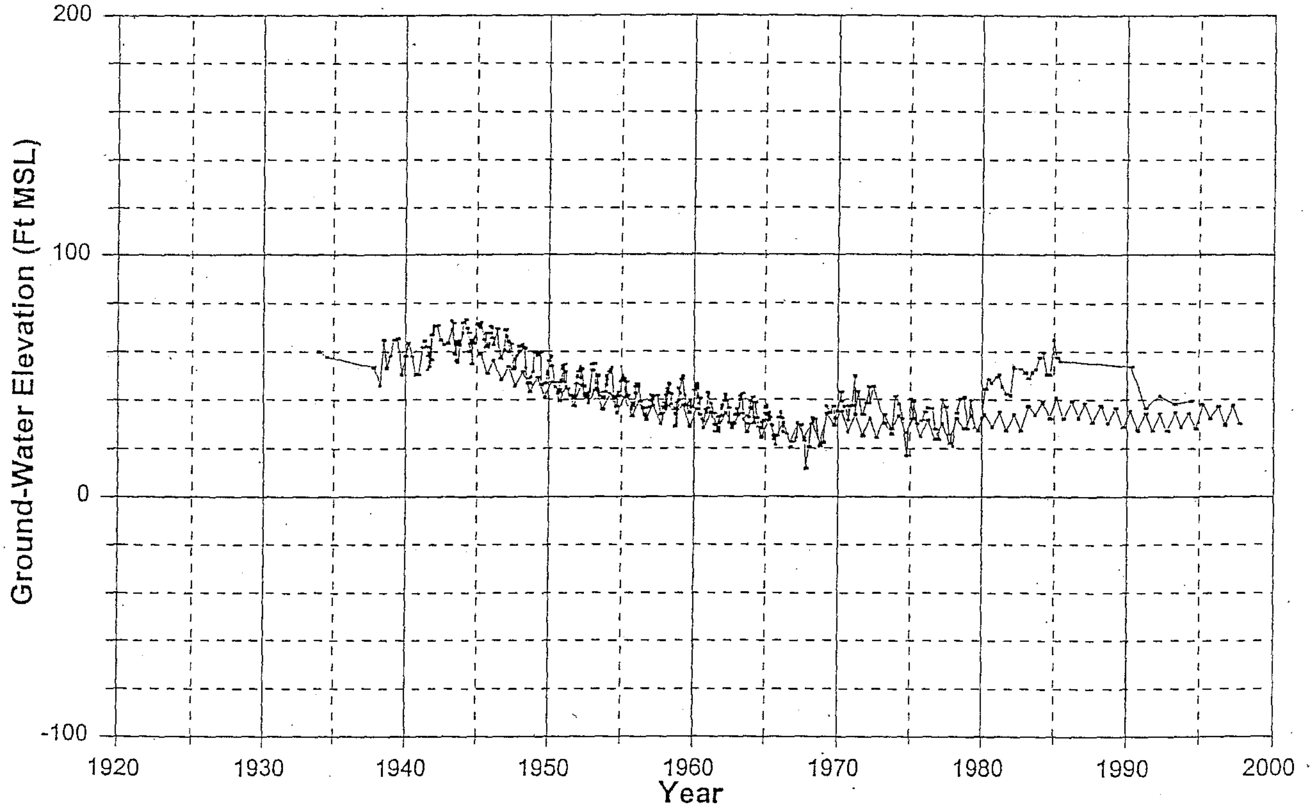

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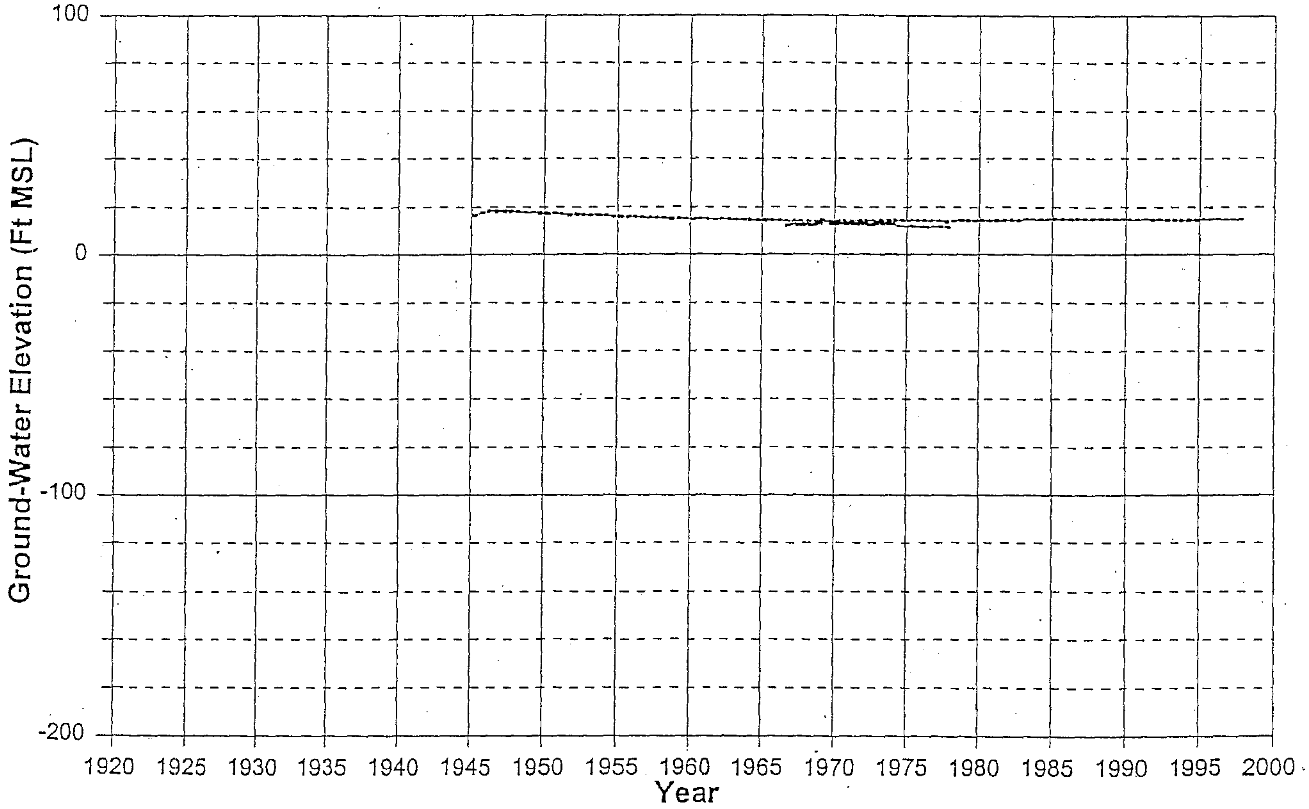

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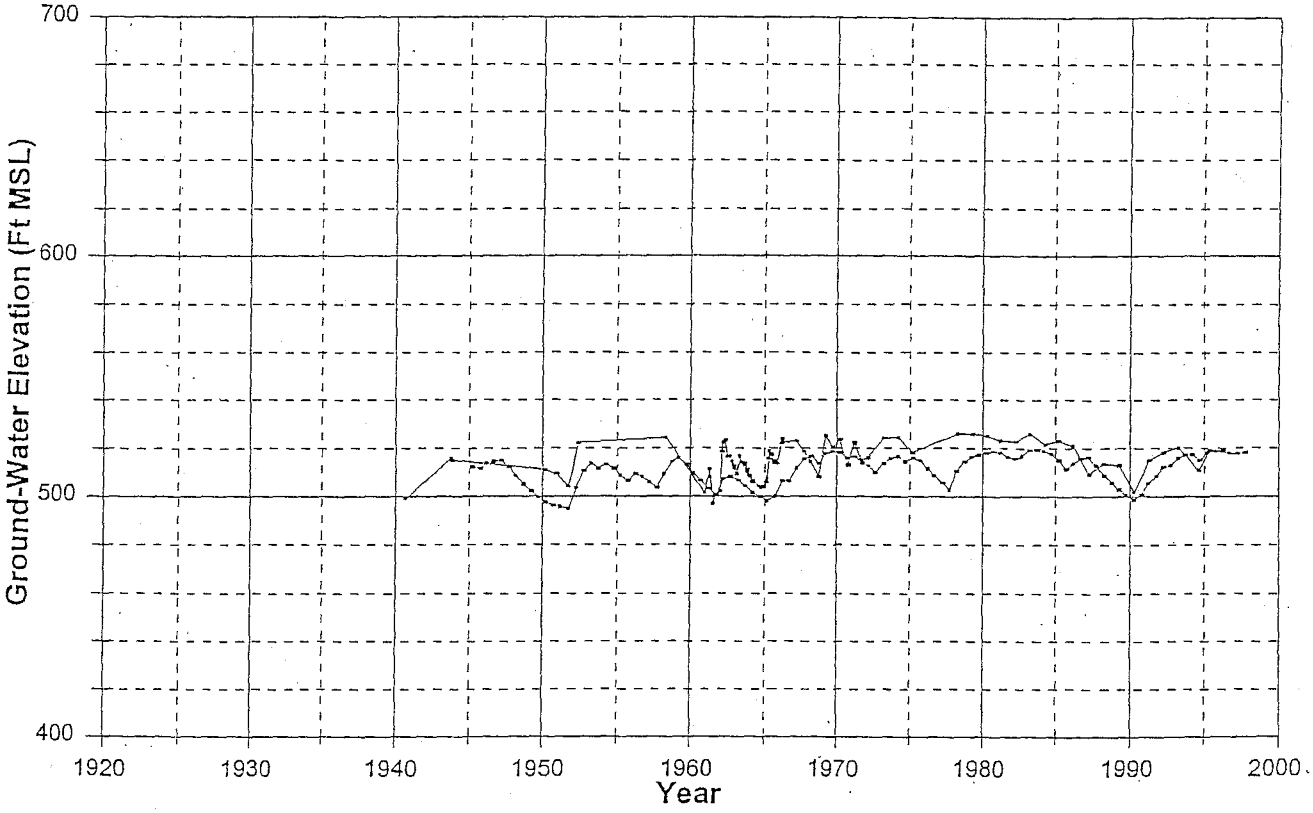

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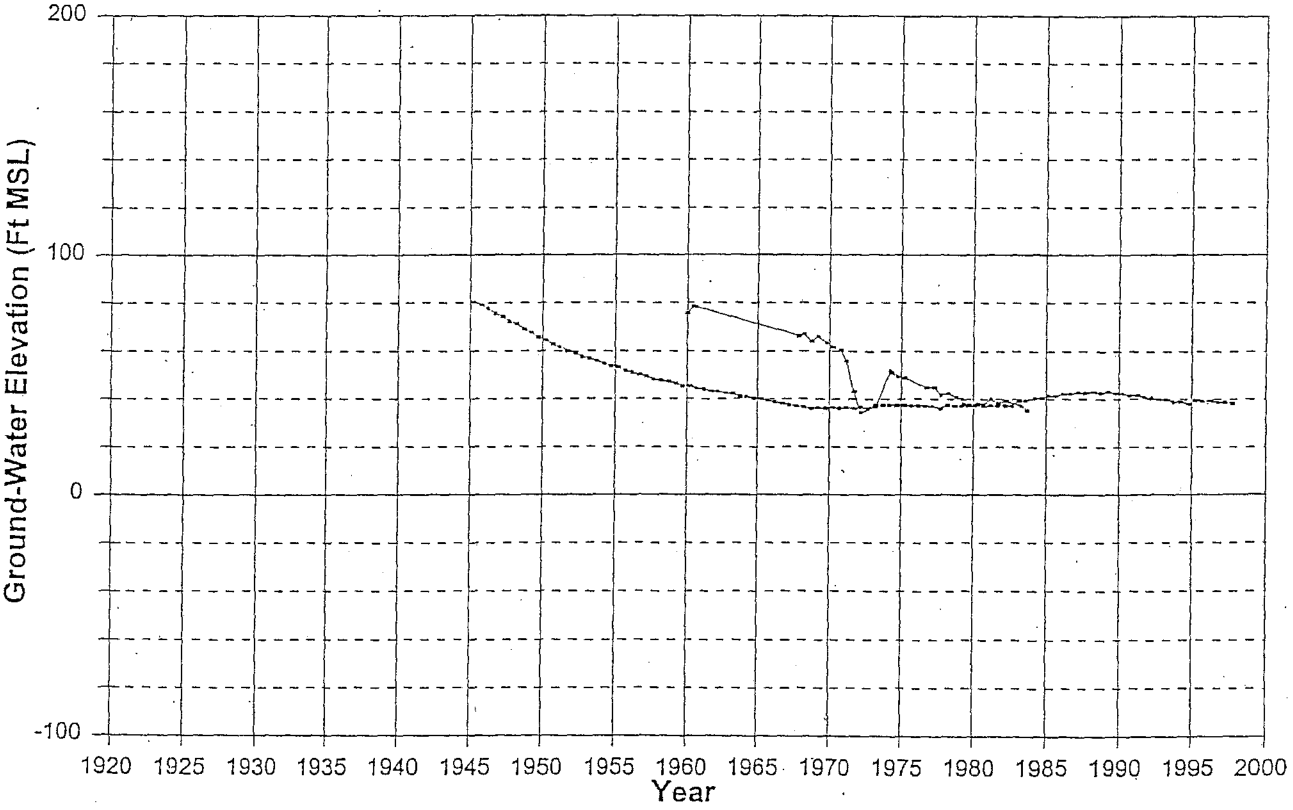

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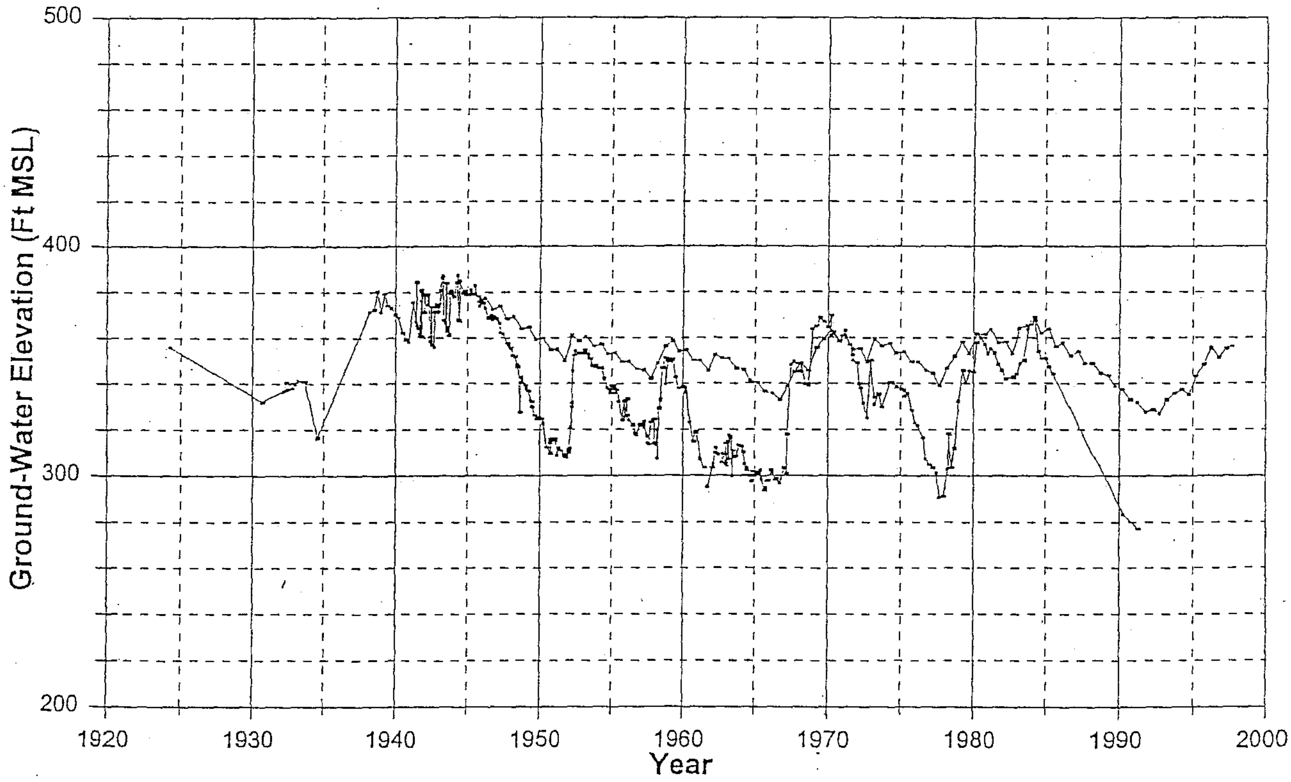

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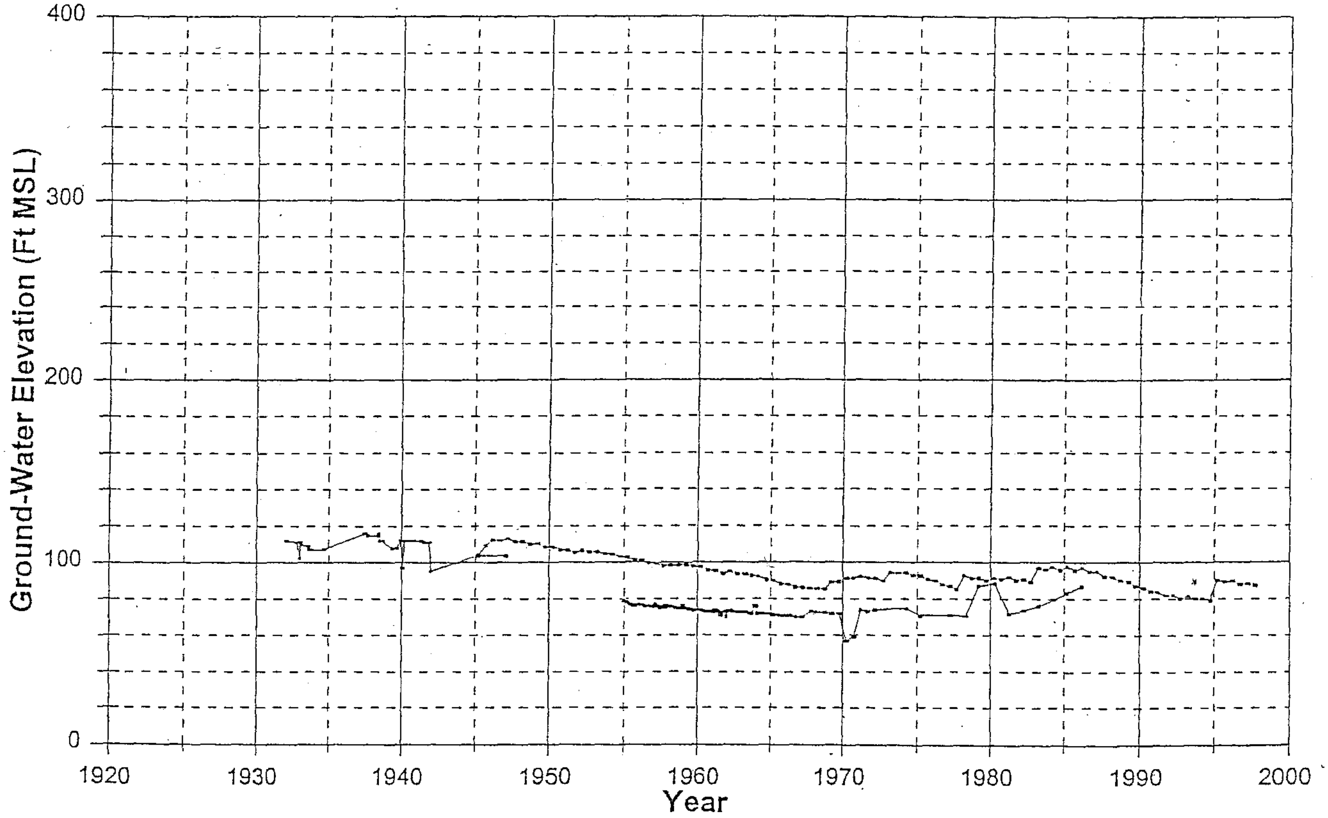

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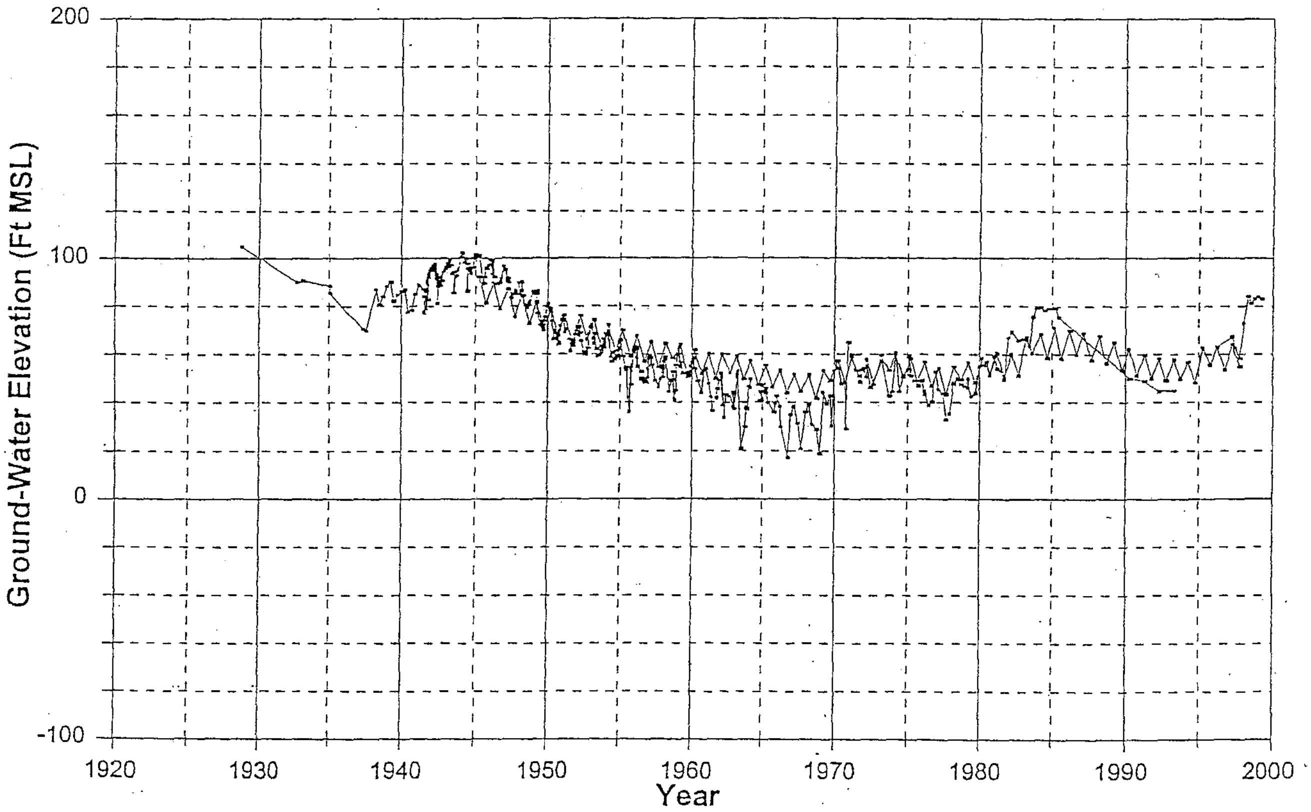

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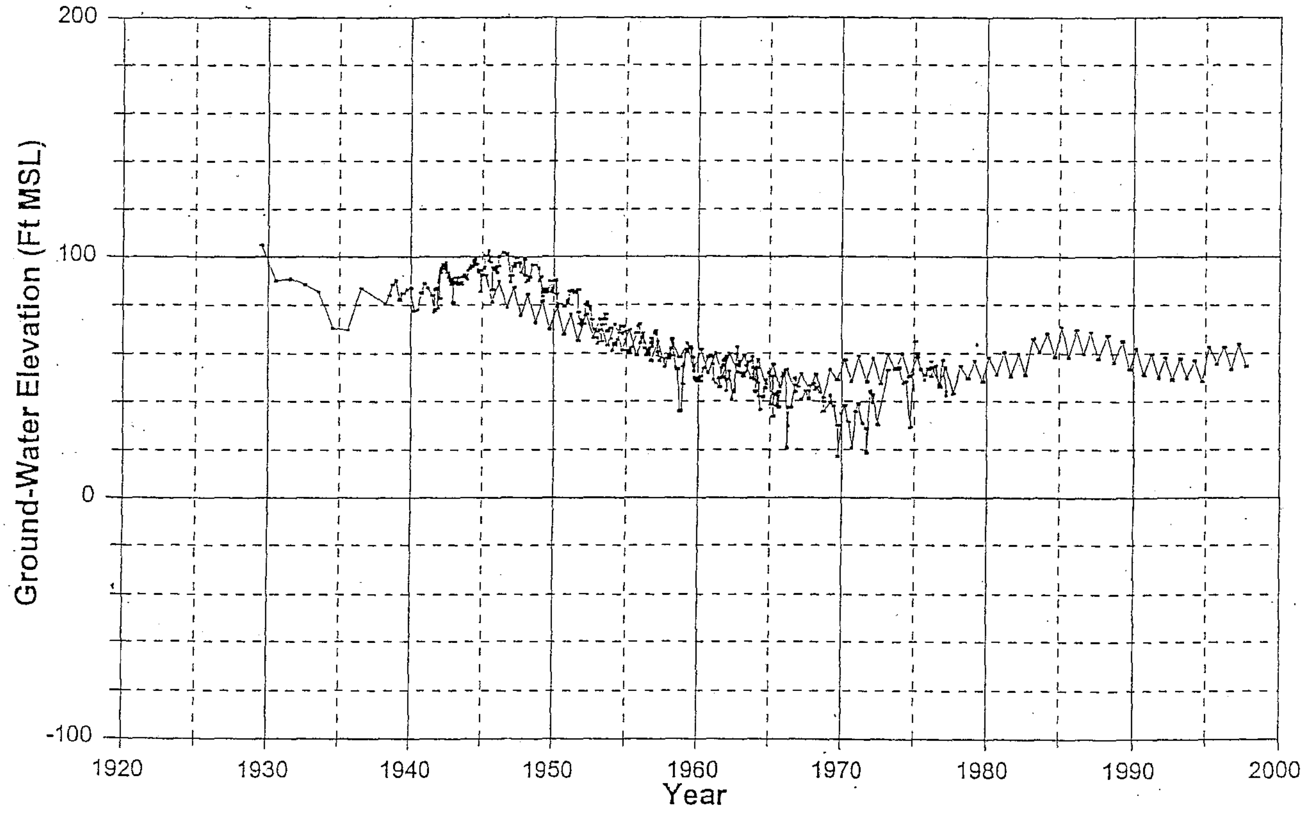

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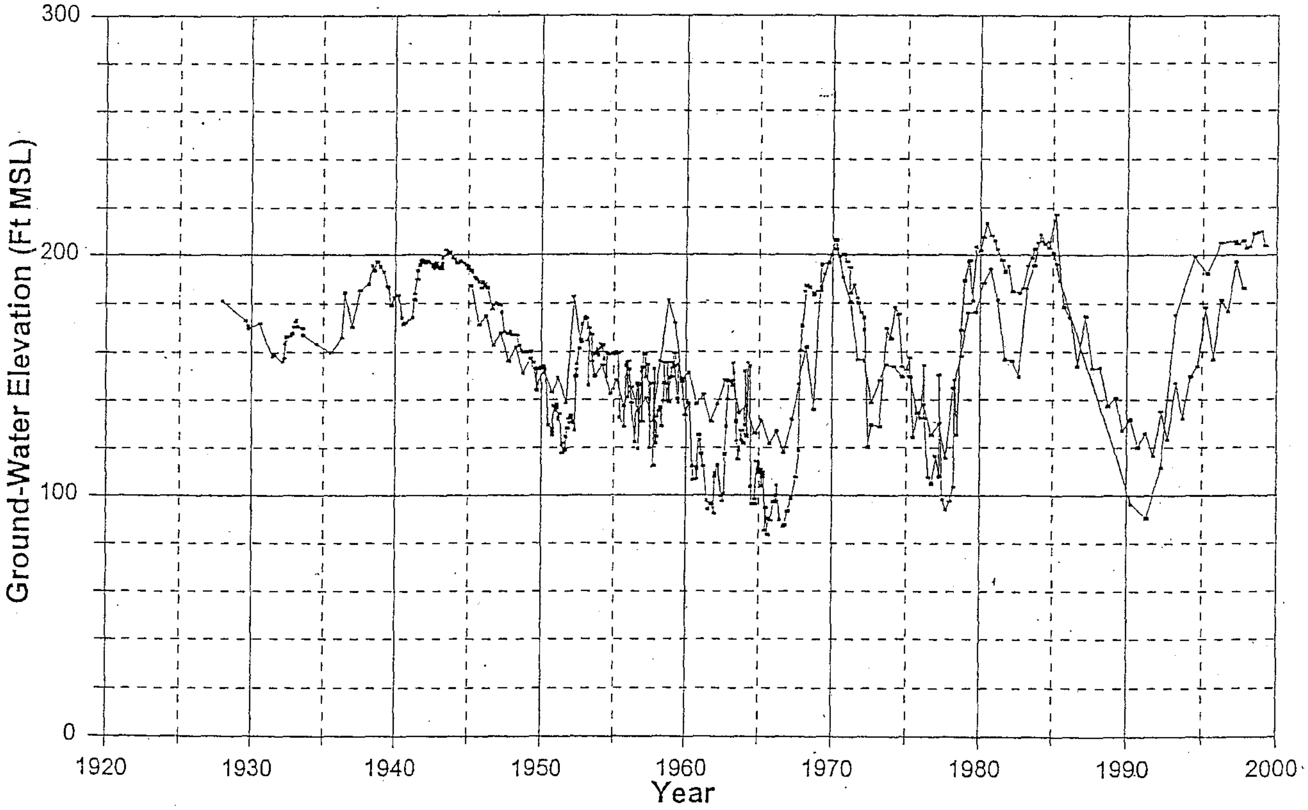

Santa Maria Valley

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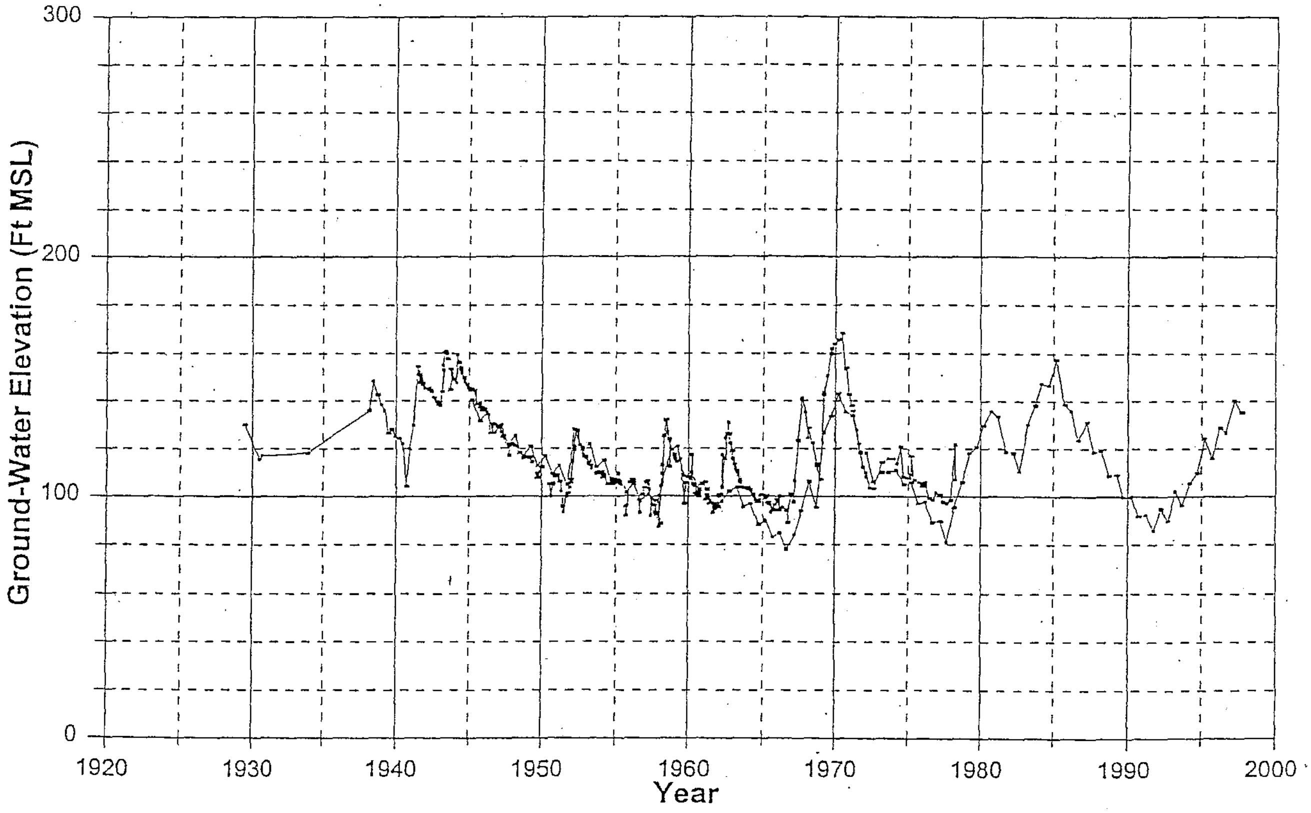

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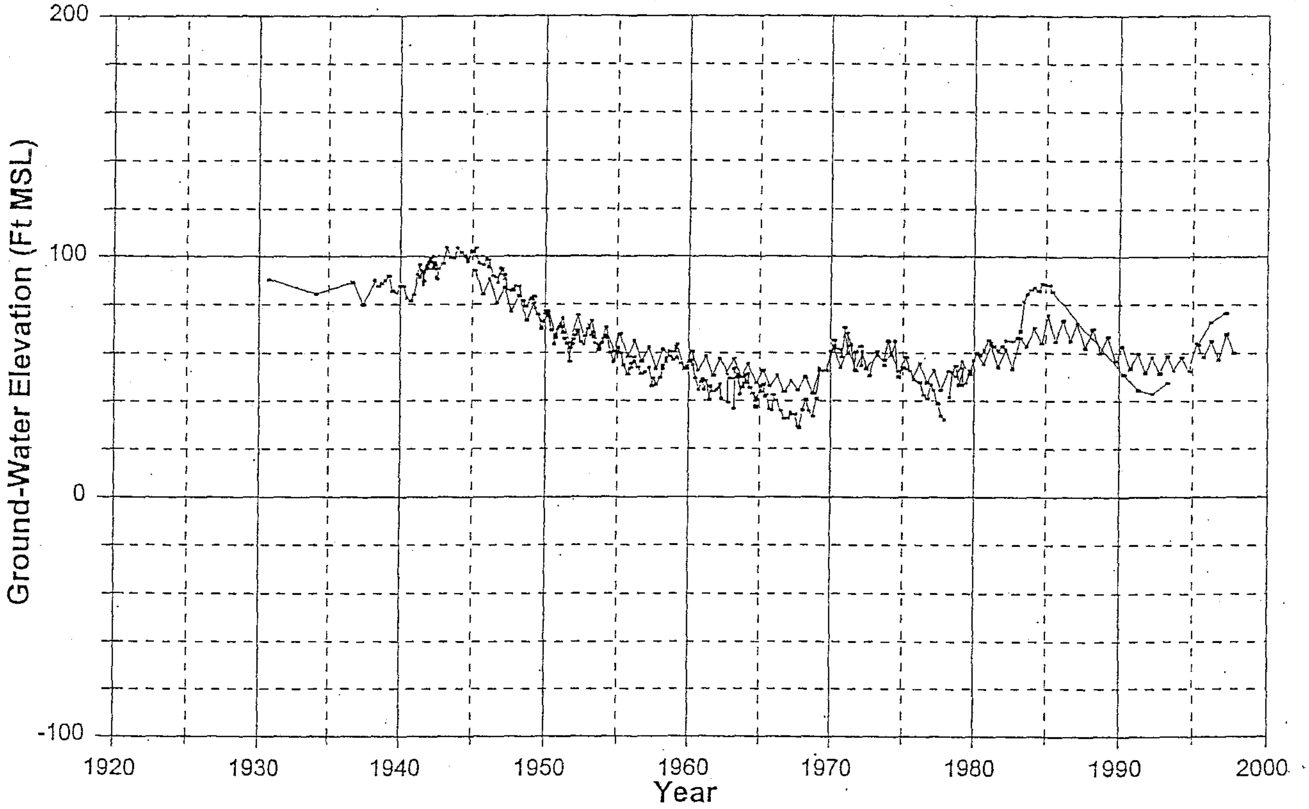

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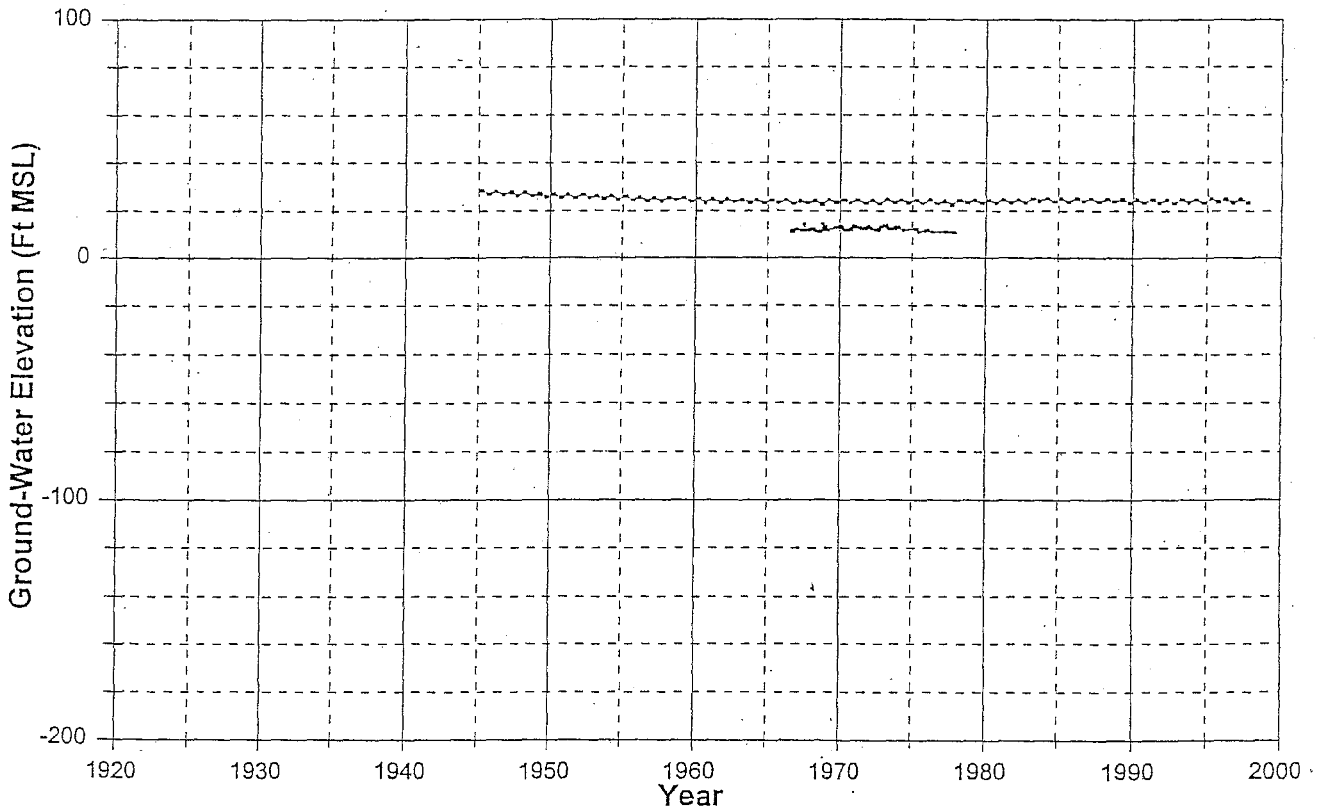

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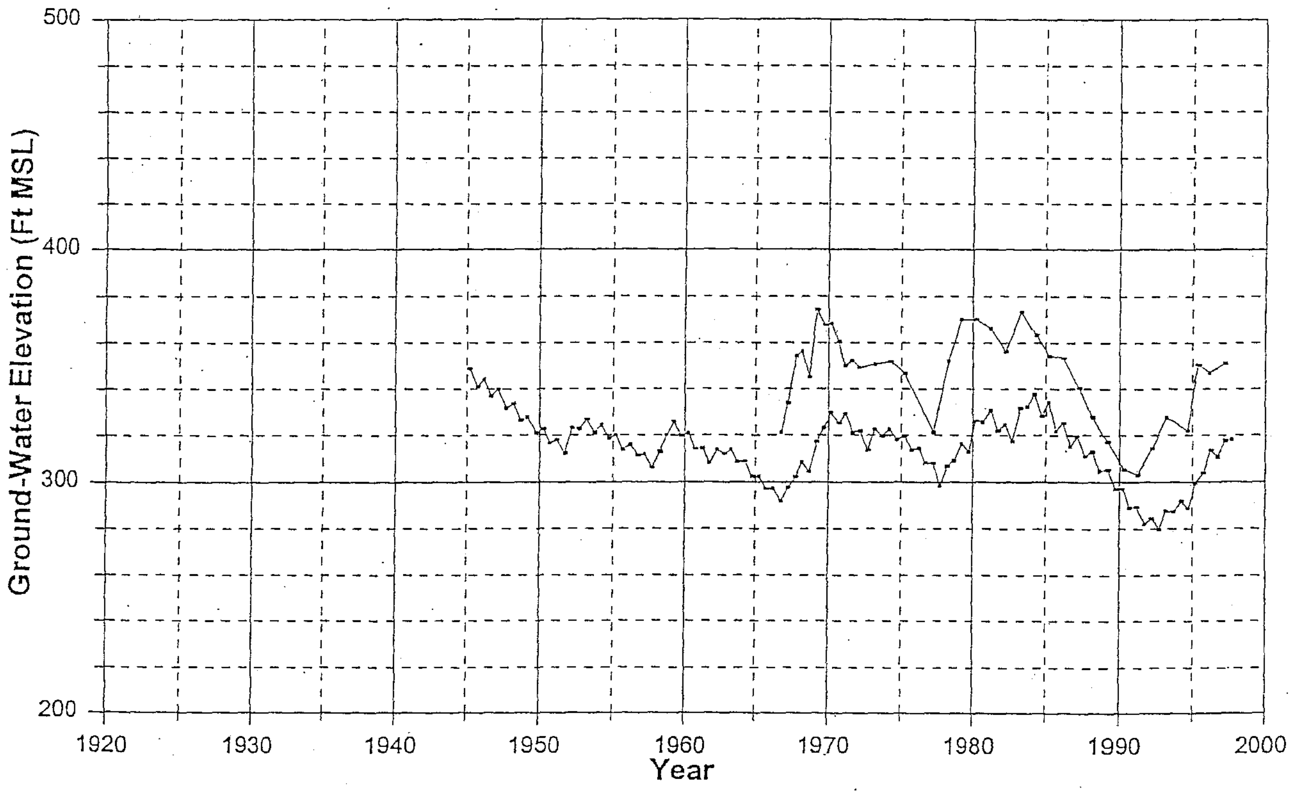

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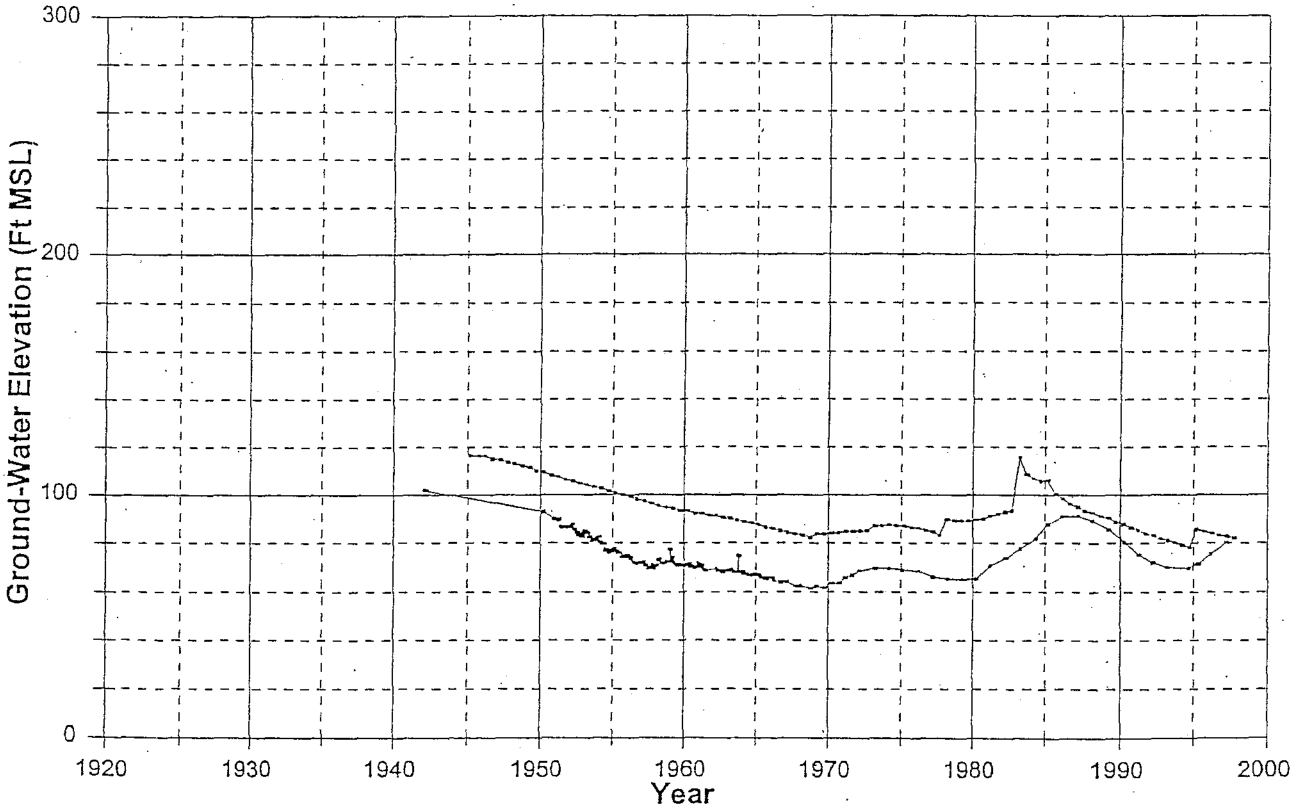

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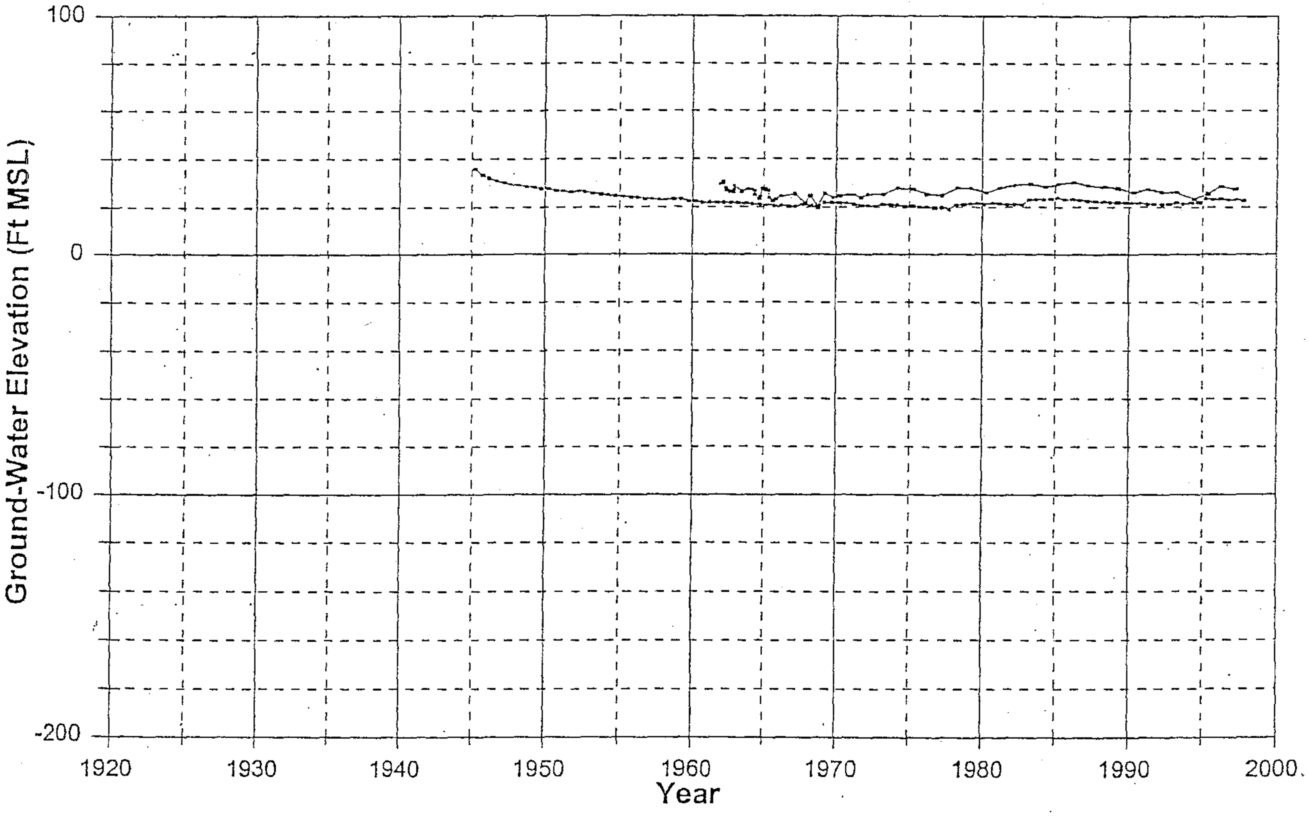

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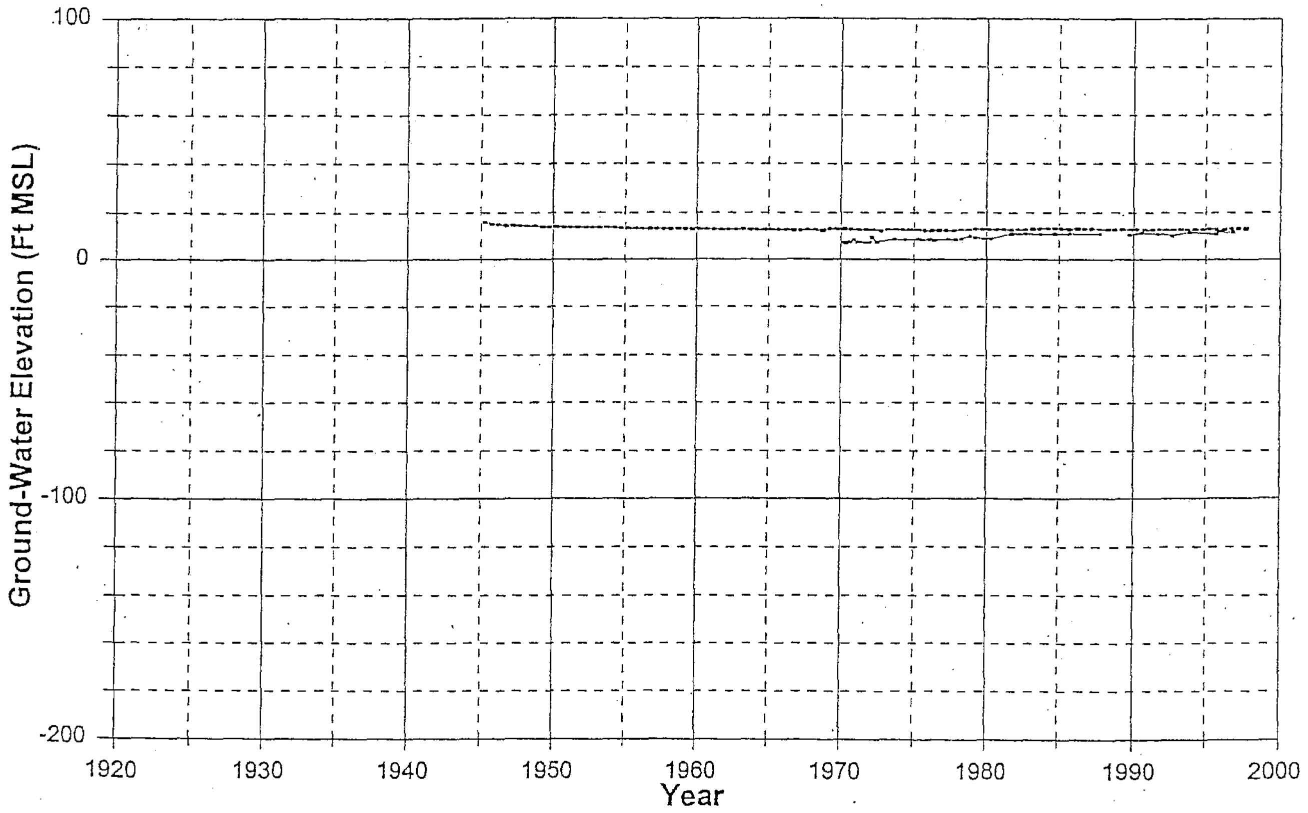

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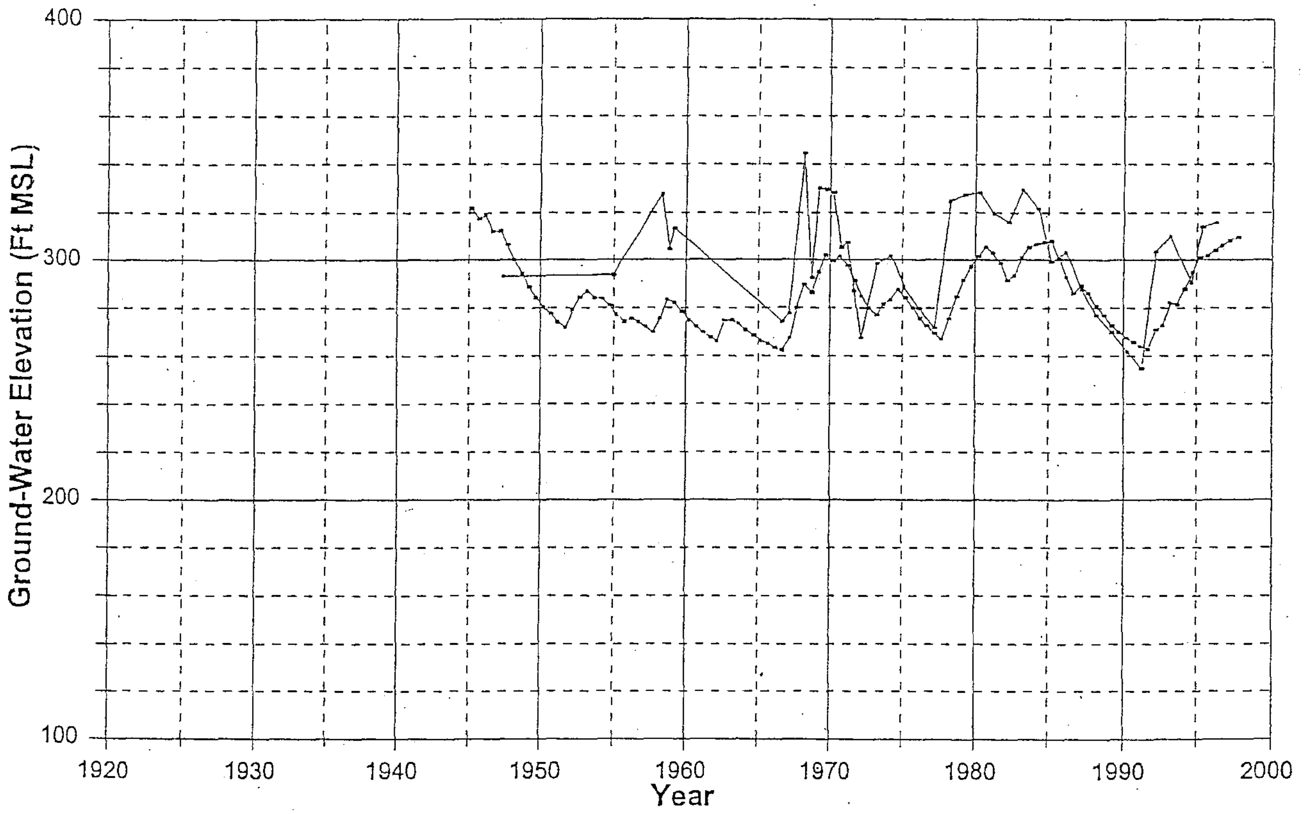

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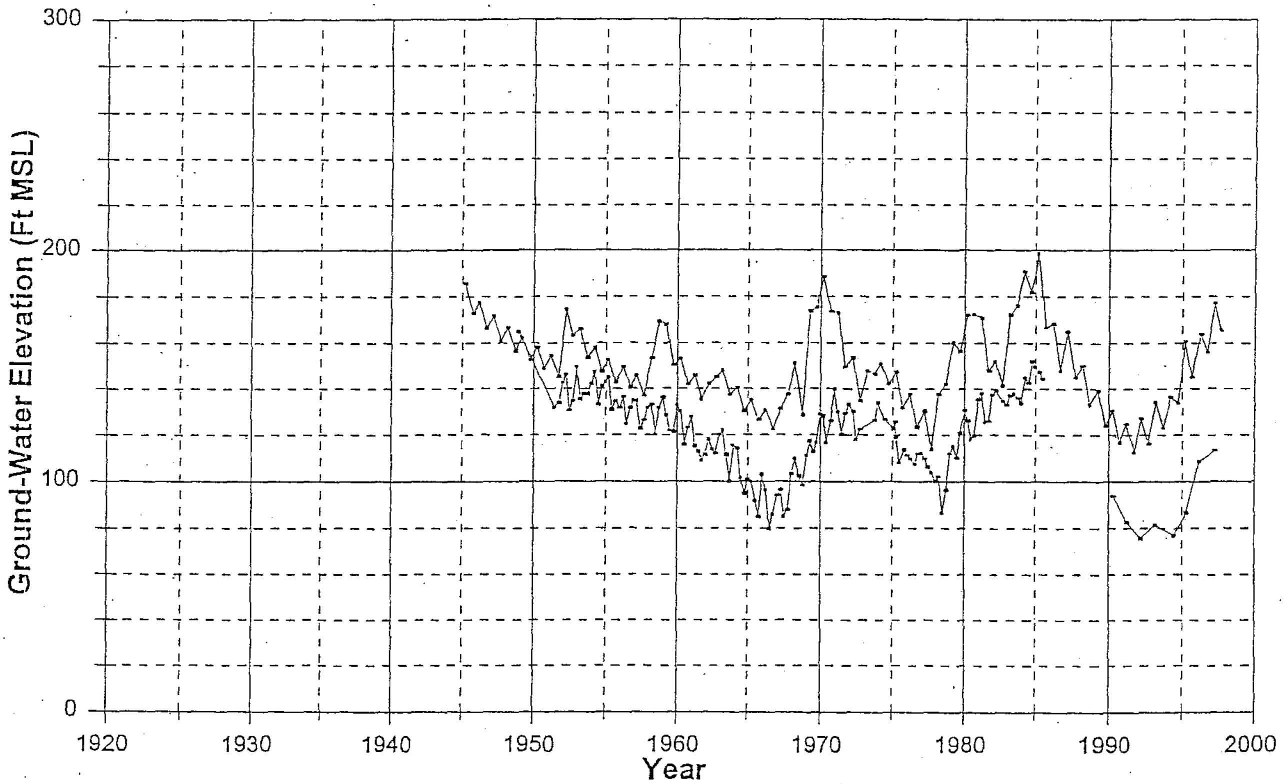
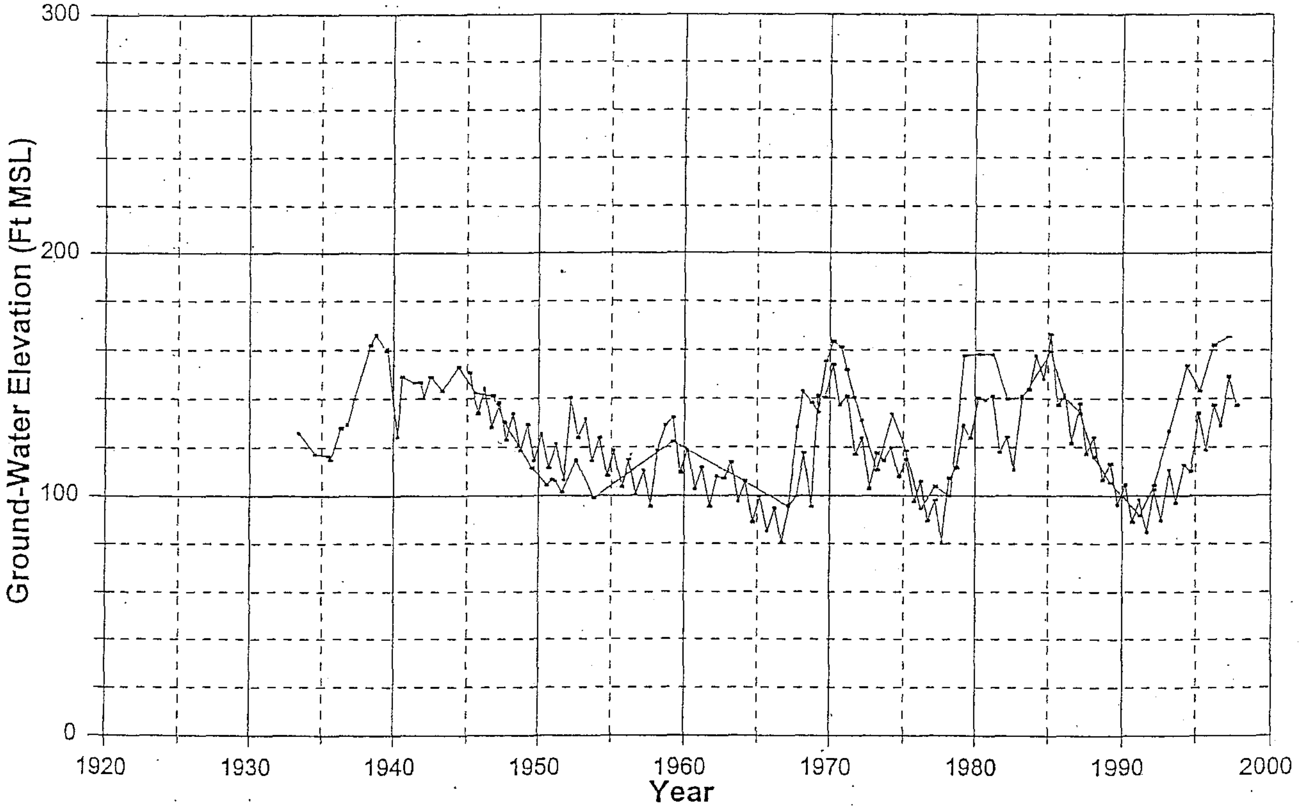


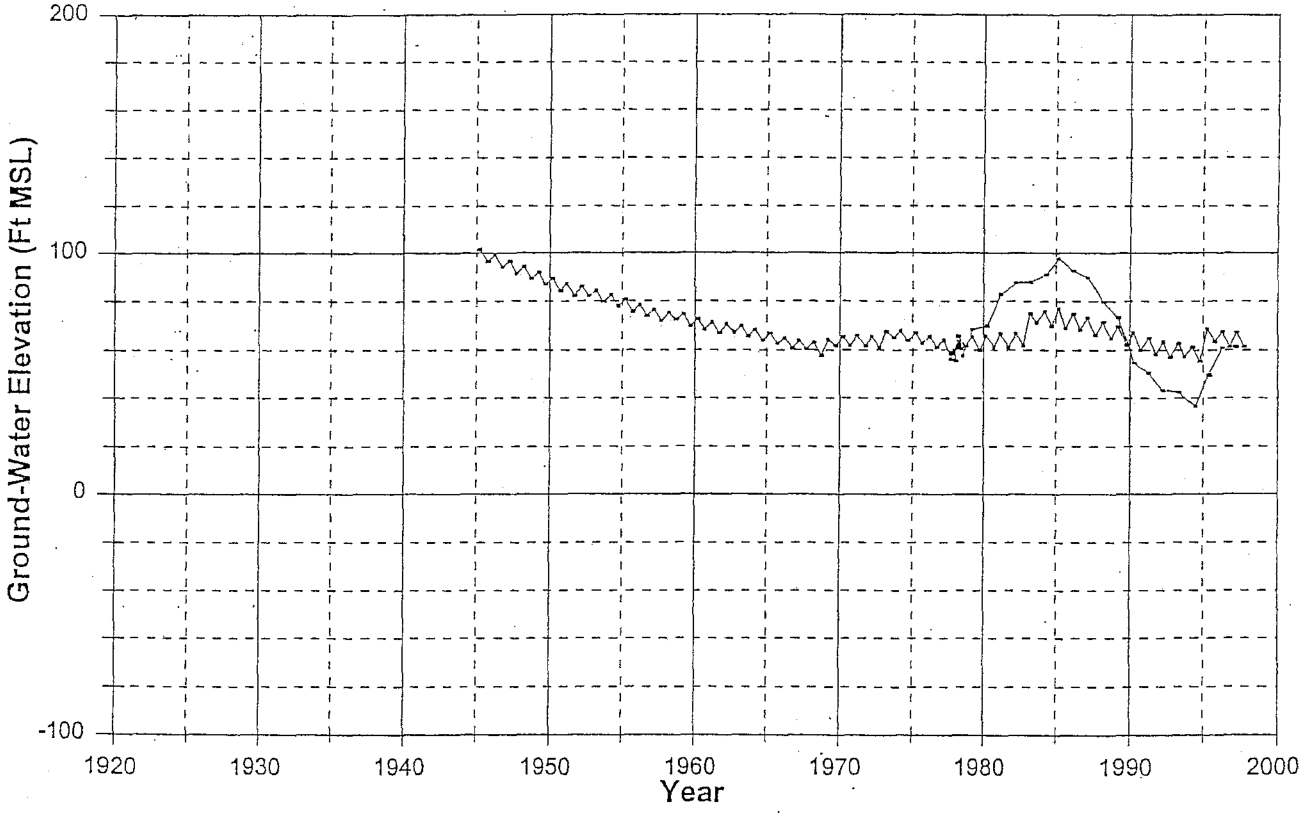
Santa Maria Valley

Well 10N/34W-13G1



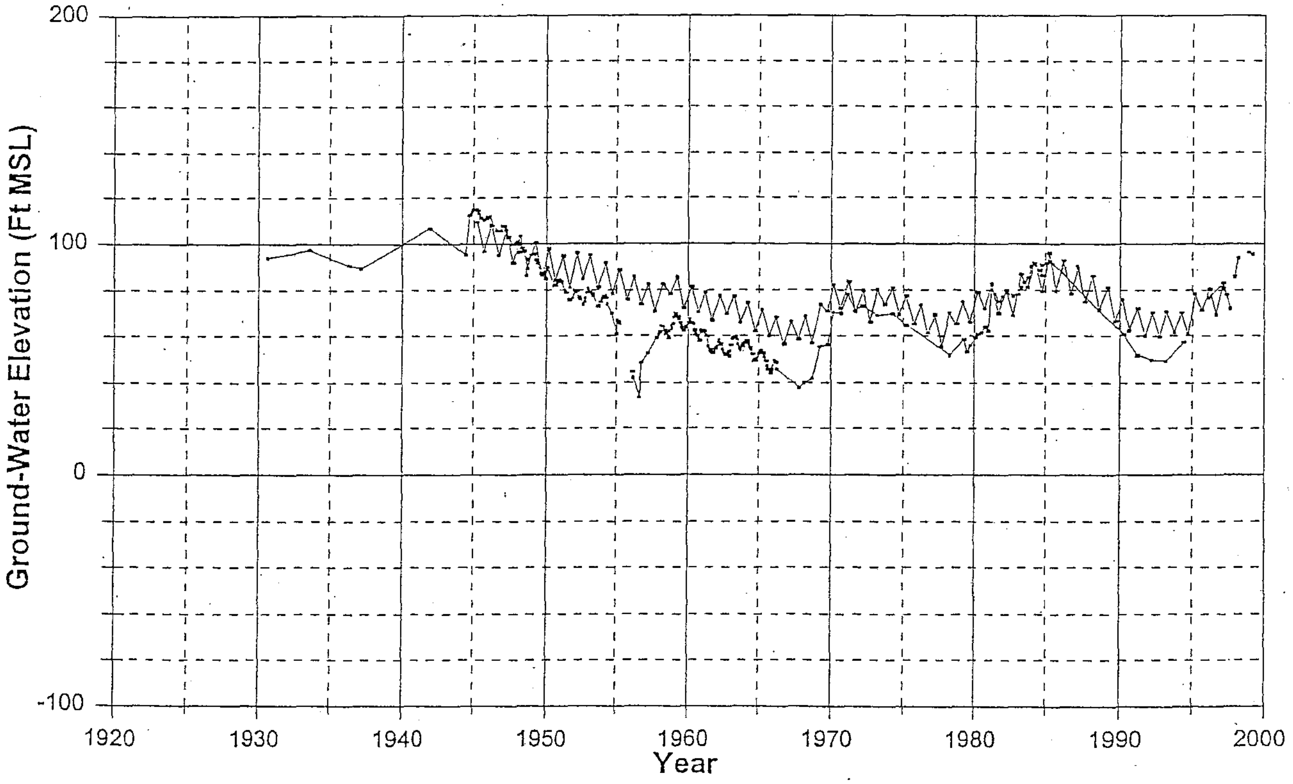
Santa Maria Valley

Well 10N/35W-35J2



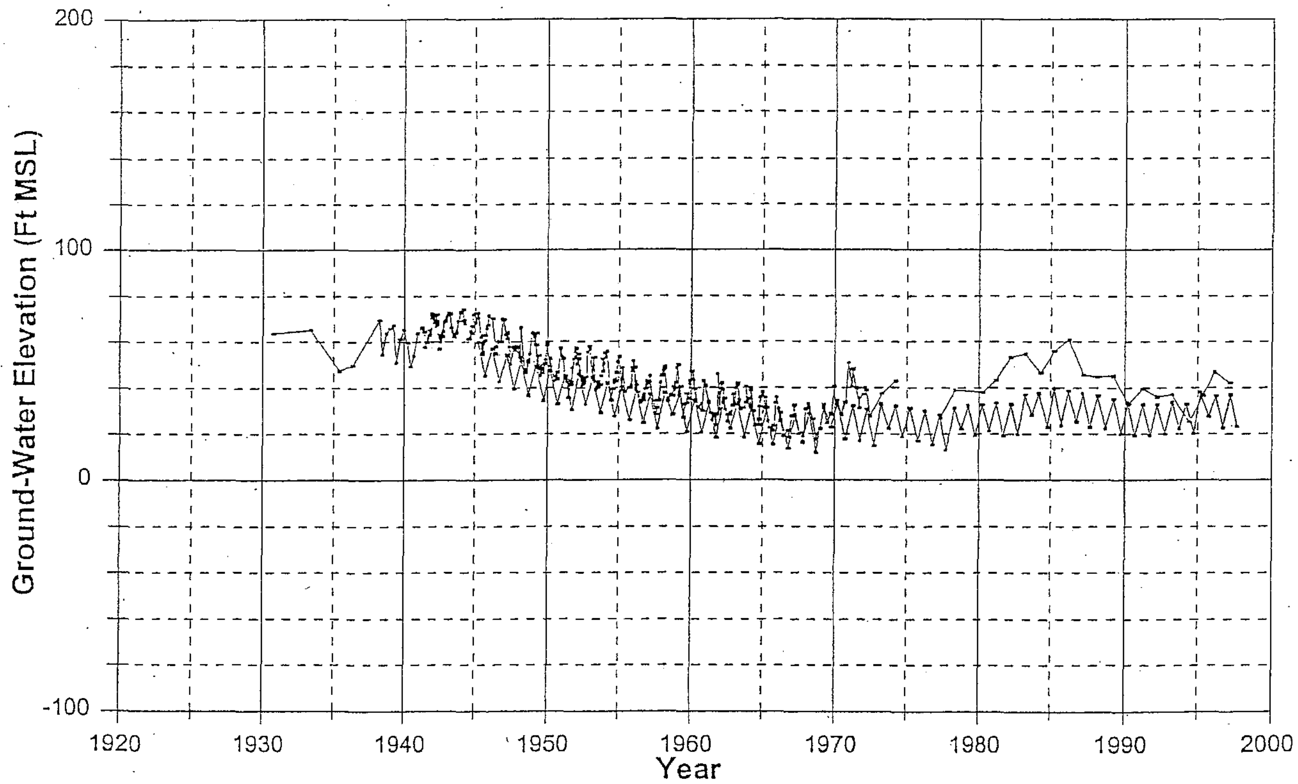
Santa Maria Valley

Well 10N/34W-20H01/H03



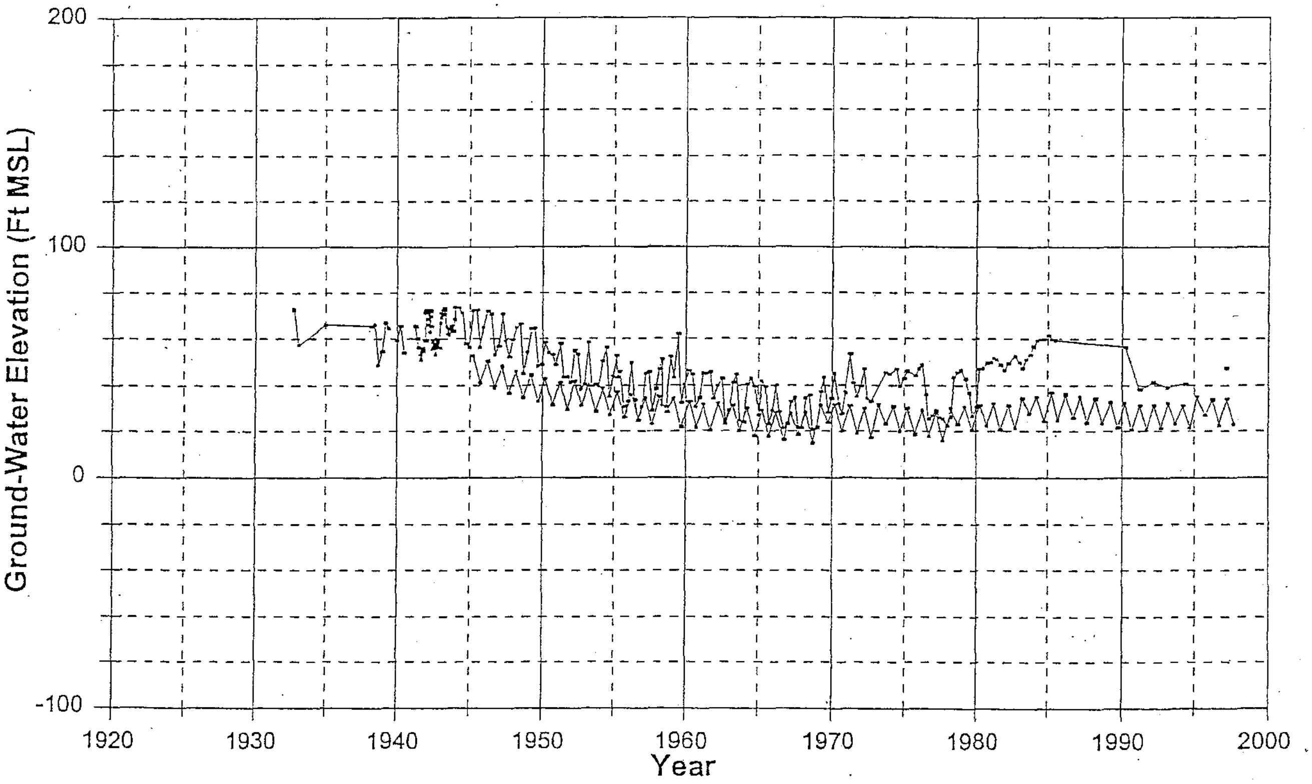
Santa Maria Valley

Well 10N/35W-09F1



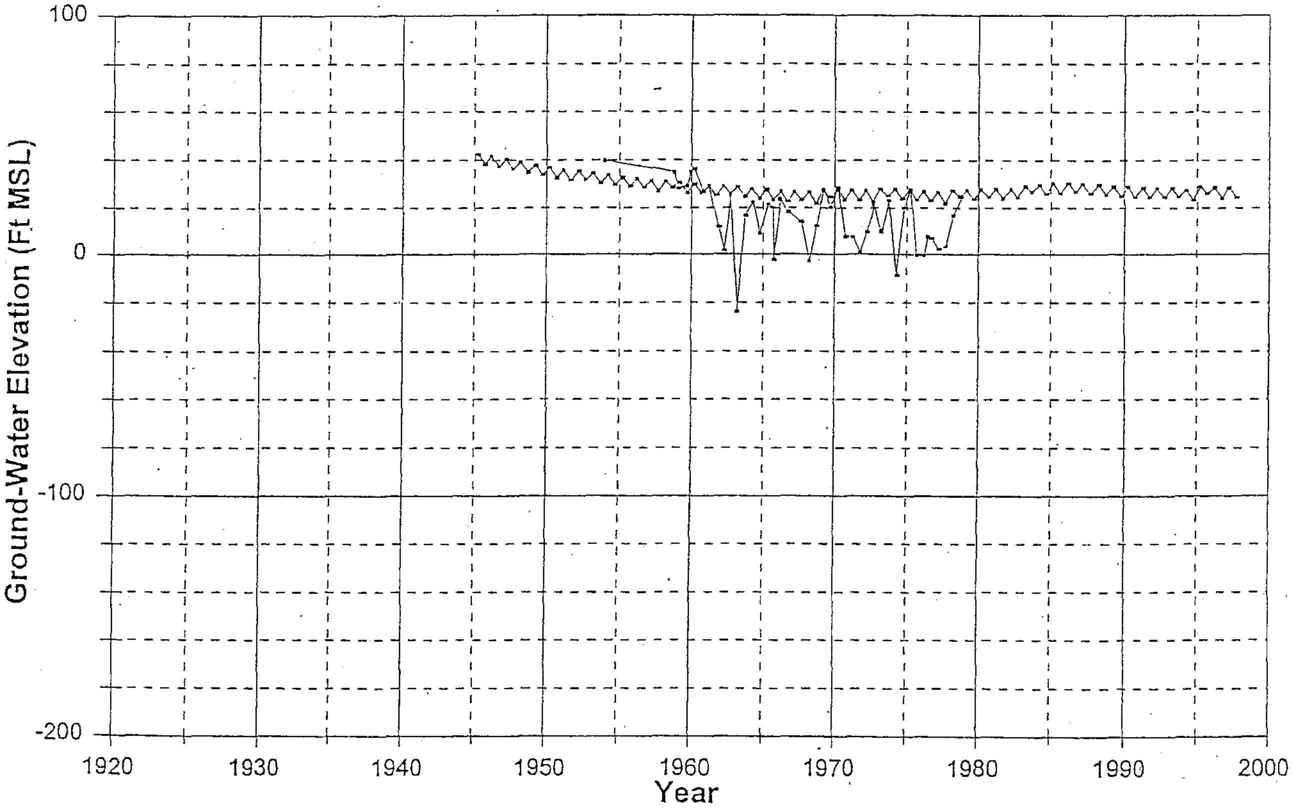
Santa Maria Valley

Well 11N/35W-28M1

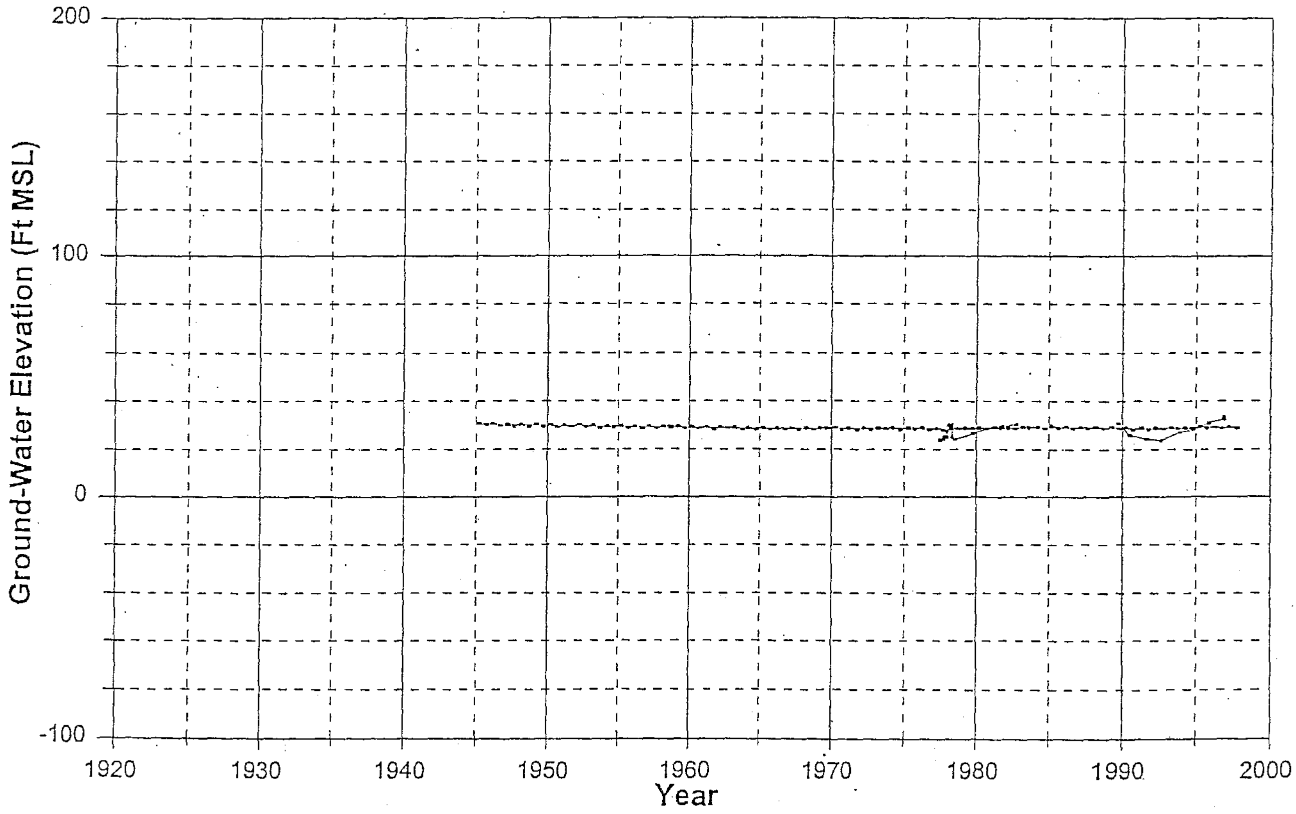


Santa Maria Valley

Well 11N/35W-07R1

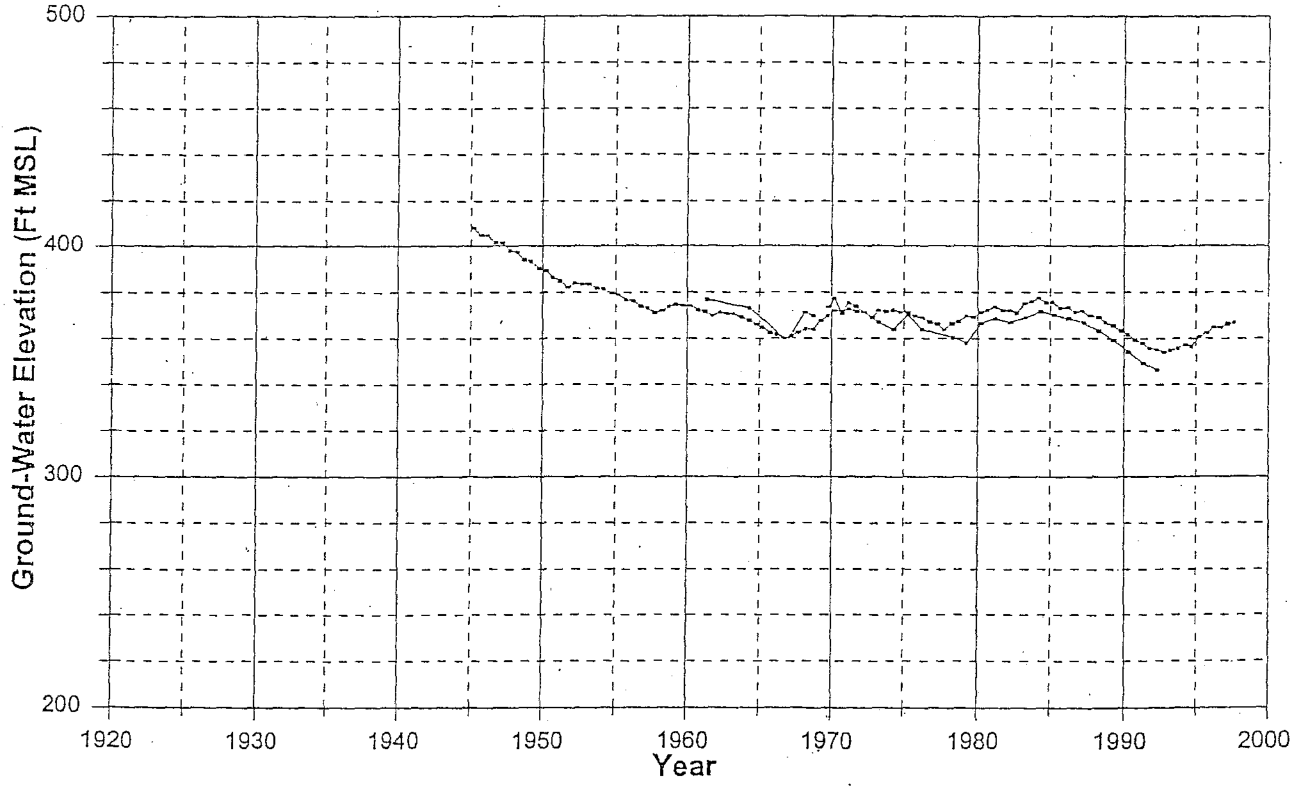


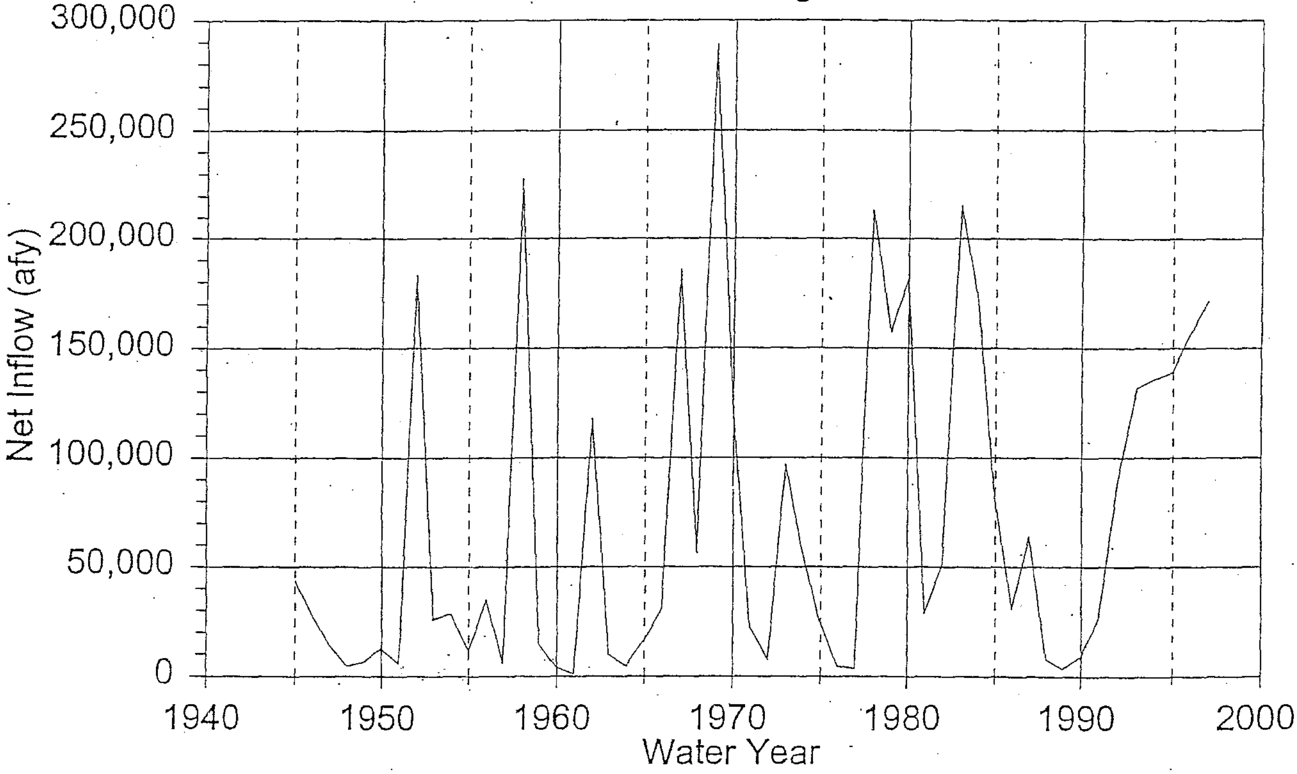
Santa Maria Valley
Well 11N/36W-35J3



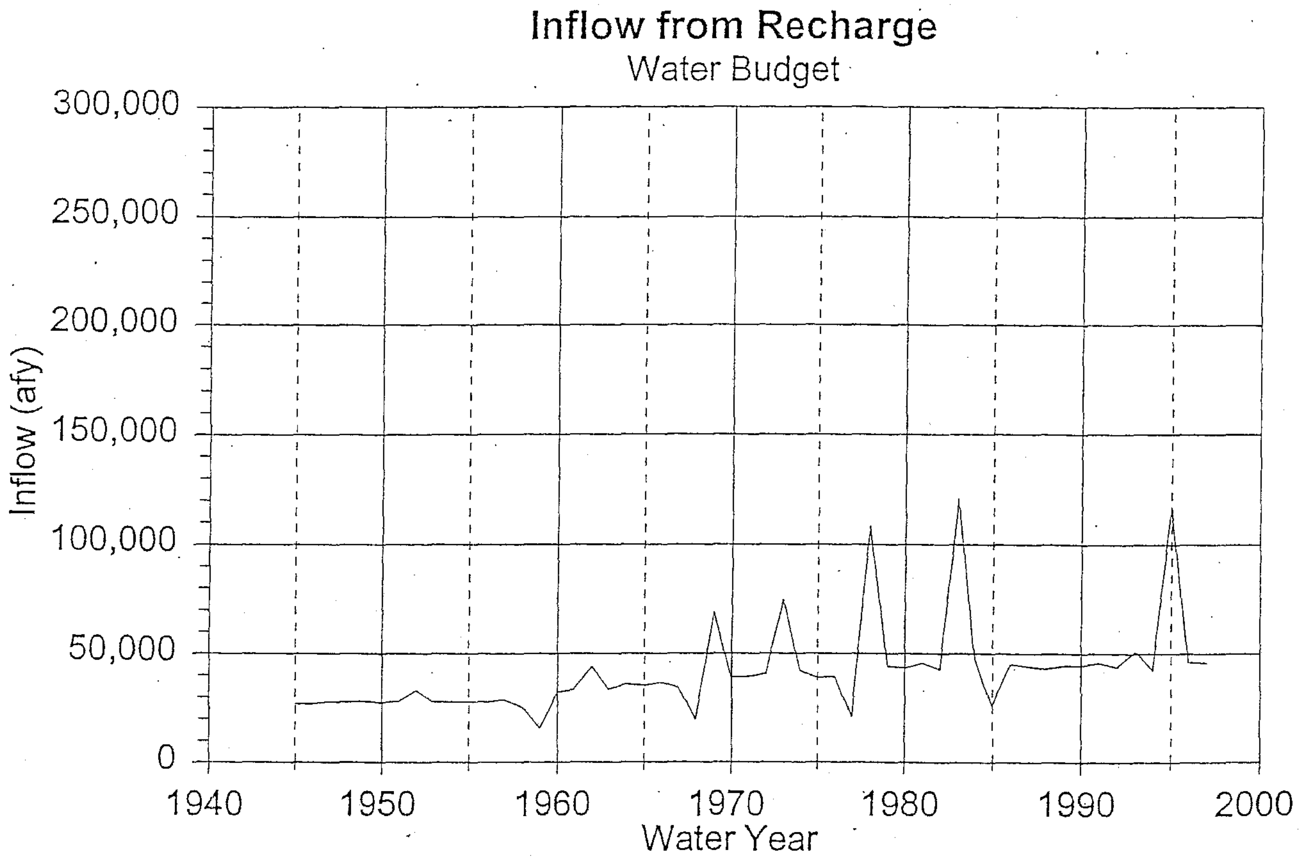
Santa Maria Valley

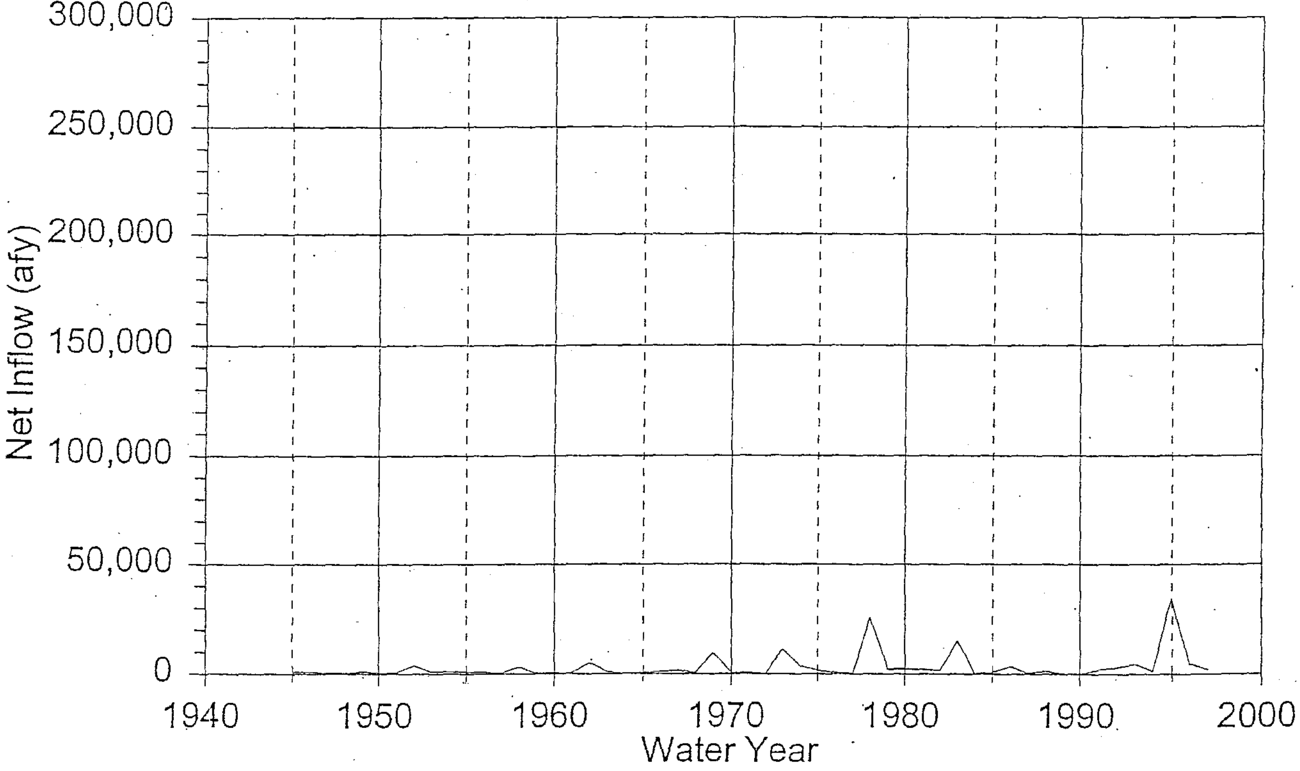
Well 9N/32W-19A1




Net Inflow from Streams

Water Budget


Inflow from Recharge
Water Budget
300,000
250,000
200,000
150,000
100,000
50,000
0
Inflow (afy)
1940
1950
1960
1970
1980
1990
2000
Water Year

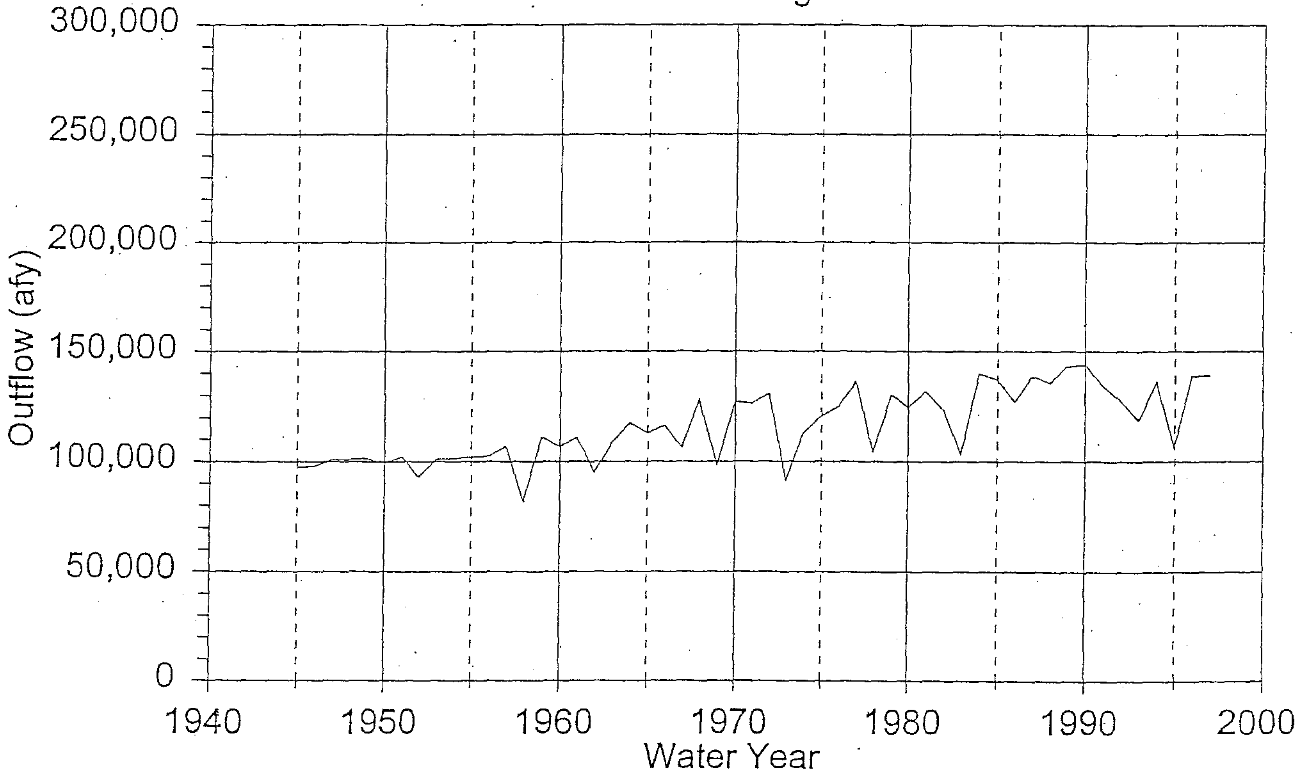


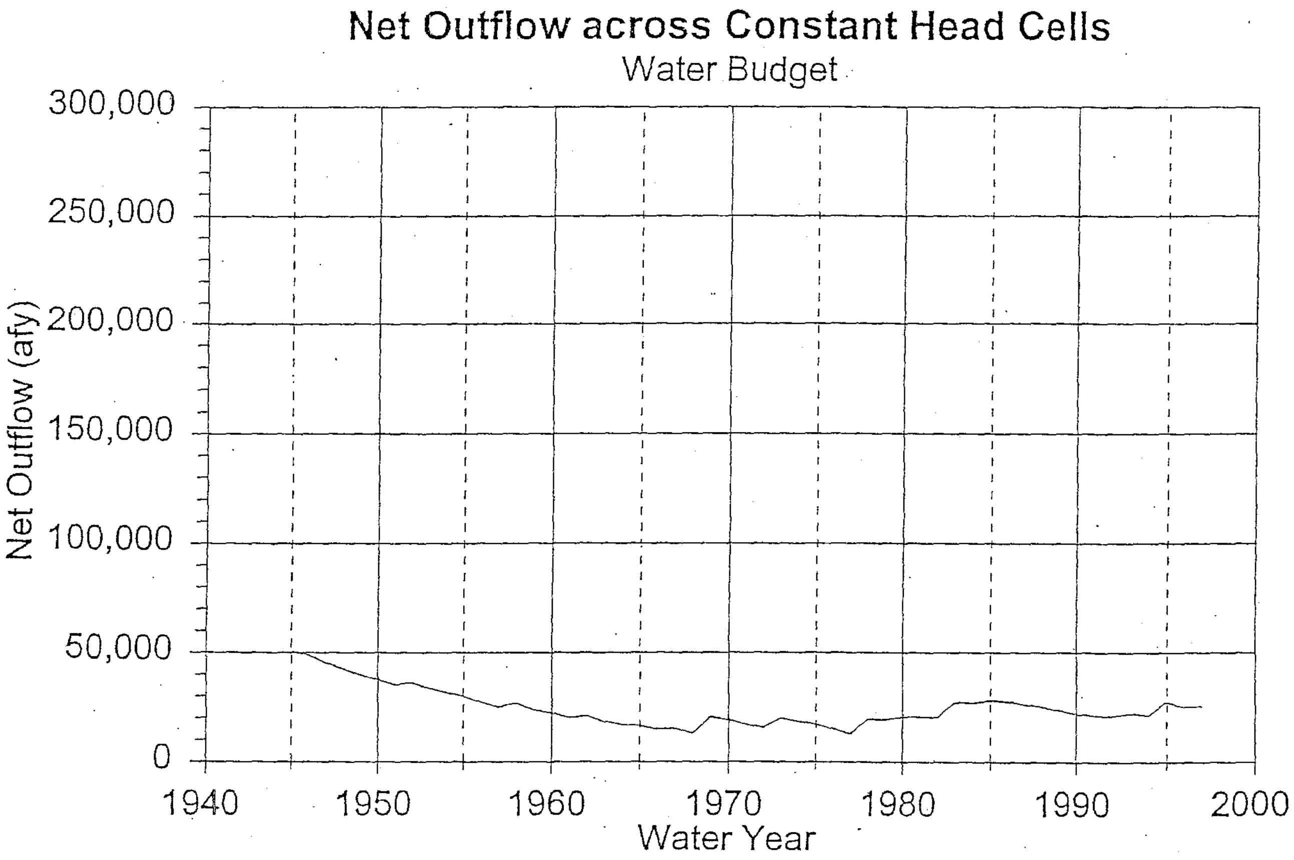
Net Inflow from River

Water Budget

Outflow to Pumpage

Water Budget





Net Outflow across Constant Head Cells

Water Budget

Net Inflow across General Head Cells

Water Budget