Geohydrology and Water Resources of the Papago Farms-Great Plain Area, Papago Indian Reservation, Arizona, and the Upper Rio Sonoyta Area, Sonora, Mexico

United States Geological Survey Water-Supply Paper 2258

Prepared in cooperation with the U.S. Bureau of Indian Affairs

Cover: Blanket and basket photo by Helga Teiwes, Arizona State Museum, University of Arizona.

The maze pattern on the basket is symbolic of the Papago philosophy of life. It tells of the complicated, difficult, and often puzzling way a man must walk to find happiness at the center of the maze. Though he seems at times to be going in the opposite direction, if man will persevere, he will find happiness and peace.

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By KENNETH J. HOLLETT

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U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2258

DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE : 1985

For sale by the
Distribution Branch, Text Products Section
U.S. Geological Survey
604 South Pickett St.
Alexandria, VA 22304

Library of Congress Cataloging in Publications Data

Hollett, Kenneth J.

Geohydrology and water resources of the Papago Farms—Great Plain area, Papago Indian Reservation, Arizona, and the upper Rio Sonoyta area, Sonora, Mexico.

(U.S. Geological Survey Water-Supply Paper 2258)
Bibliography: p. 42-43
Supt. of Docs. no.: I 19.13:2258
1. Water, underground—Arizona—Papago Indian Reservation. 2. Water, underground—Sonoyta River Region (Mexico and Ariz.). 3. Water-supply—Arizona—Papago Indian Reservation. 4. Water-supply—Sonoyta River Region (Mexico and Ariz.). I. United States. Bureau of Indian Affairs. II. Title. III. Series: United States. Geological Survey. Water-Supply Paper 2258.

GB1025.A6H65 553.7'9'0979177 84-600104

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Geohydrology and Water Resources of the Papago Farms-Great Plain Area, Papago Indian Reservation, Arizona, and the Upper Rio Sonoyta Area, Sonora, Mexico

By Kenneth J. Hollett

Abstract

The Papago Farms-Great Plain and upper Rio Sonoyta study area includes about 490 square miles in south-central Arizona and north-central Sonora, Mexico. The area is characterized by a broad, deep, sediment-filled basin bounded by low, jagged fault-block mountains. The climate is arid to semiarid. The climate and abundant ground water provide favorable conditions for irrigated agriculture. Annual precipitation averages 5 to 8 inches per year on the desert floor. Runoff, which occurs as intermittent streamflow and sheetflow, is too short lived and too laden with suspended sediment to be a reliable source for irrigation or public supply.

Nearly all the water used to irrigate more than 5,000 cultivated acres in the study area is withdrawn from the unconsolidated to partly consolidated basin fill. The ground water occurs in the deposits under unconfined (water-table) conditions with a saturated thickness that ranges from zero along the mountain fronts to more than 8,000 feet in the center of the basin. The amount of recoverable ground water in storage to a depth of 400 feet below the 1978-80 water table is estimated to be about 10 million acre-feet. Depths to water range from about 500 feet near the southern boundary of the study area to about 150 feet in the center of the study area. Ground water enters the area principally as underflow beneath the San Simon and Chukut Kuk Washes and as recharge along the mountain fronts. On the basis of model results, annual inflow to the ground-water system is estimated to be about 4,390 acre-feet. Ground water moves through the study area along paths that encircle a virtually impermeable unit in the basin center, termed "the lakebed-clay deposits," and moves westward to an outflow point beneath the Rio Sonoyta south of Cerro La Nariz. Rates of water movement range from less than 1 foot per year in clays to about 160 feet per year in well-sorted, coarse stream-channel deposits.

Transmissivities along the basin margins range from 10,000 to 40,000 feet squared per day, whereas transmissivities in the basin-center lakebed-clay deposits are estimated to be less than 100 feet squared per day. Most wells that are located along the basin margin and tap more than 300 feet of saturated basin fill in the upper 1,000 feet of the aquifer should yield from 500 to 3,000 gallons per minute to properly constructed and developed wells. Specific capacities should range from 10 to 50 gallons per minute per foot of drawdown.

The water in the aquifer is moderate to poor in chemical quality for irrigation and public-supply use. The ground water is mainly a sodium bicarbonate type with dissolved-solids concentrations that range from about 250 to 5,000 milligrams per liter and average about 530 milligrams per liter. The poorest quality water is associated with the basin-center lakebed-clay deposits. In most of the basin, the water contains fluoride concentrations that exceed the maximum contaminant levels acceptable for drinking water. Waters from the basin-center lakebed-clay deposits are also anomalously high in dissolved arsenic and unacceptable for public supply. High concentrations of sodium and bicarbonate in the ground water of the study area present potential hazards to most crops, and the use of this type of water requires careful farm-management practices.

In 1981 outflow resulting from withdrawals of water from the aquifer was about 23,700 acre-feet. Storage is being depleted at a rate of about 19,000 acre-feet per year. On the basis of a mathematical simulation of the ground-water system and withdrawal rates in 1981, storage depletion and drawdown of the water table were projected to 1991. Water-level declines in 1991 were estimated to be as much as 20 feet at Papago Farms and more than 40 feet in the area south of the basin-center lakebed-clay deposits. The estimated amount of depletion in 1991 of ground water stored in the upper 400 feet of the aquifer is less than 3.0 percent of the total amount in storage. Ground-water withdrawals in the upper Rio Sonoyta area do not appear to have an effect on water levels in the Papago Farms-Great Plain area. The virtually impermeable basin-center lakebed-clay deposits act as a ground-water barrier between Papago Farms and irrigated areas to the south.

INTRODUCTION

The Papago Farms-Great Plain and upper Rio Sonoyta study area includes about 490 mi^2 in the Rio Sonoyta drainage basin in south-central Arizona and north-central Sonora, Mexico (fig. 1). The climate is arid to semiarid. The climate and abundant ground water provide favorable conditions for irrigated agriculture. In 1981 the Papago Tribe of Arizona farmed about 1,200 acres at Papago Farms. Irrigated acreage in the Sonoran part of the study area is estimated to be about 4,000 acres. Streamflow is intermittent, unpredictable, and not a dependable source of water for irrigation or public supply. Irrigation and public-supply requirements, therefore, are wholly dependent on ground water. The water-resource appraisal was prompted by the increased demand for ground water to meet the growing irrigation and public-supply requirements in the study area.

Purpose of Investigation and Scope of Report

The purpose of this investigation was to evaluate the availability and quality of surface water and ground water in the study area and to determine the impact that increased agricultural development would have on future availability of water. Virtually all the water used for irrigation is withdrawn from the subsurface; therefore, the main emphasis of the study was directed toward evaluating the ground-water system. Surface-water runoff was evaluated to determine the possibility of developing a supplemental irrigation source for Papago Farms. The study was done in cooperation with the U.S. Bureau of Indian Affairs on behalf of the Papago Tribe of Arizona.

In order to adequately define the hydrologic system, new hydrologic, geologic, and geophysical data were collected and past data were reevaluated. This report describes the hydrologic system of the study area, particularly the physical constraints of the ground-water flow system. Chemical quality of ground water is presented to evaluate the suitability of ground water for irrigation and public supply and also to confirm ground-water flow patterns as related to changes in water quality. Quantity and chemical quality of surface water are tabulated and discussed in order to evaluate the use of surface water as a possible supplementary irrigation source. A ground-water budget summarizing the amount of ground water that enters, leaves, and is stored was developed for the study area. A numerical ground-water flow model was developed to test and evaluate the ground-water system and to simulate the effects of withdrawal of ground water near Papago Farms.

Geographic Setting

The study area consists of the Papago Farms-Great Plain area and the upper Rio Sonoyta area. The Papago Farms-Great Plain area is north of the international boundary and within the Papago Indian Reservation; the upper Rio Sonoyta area is south of the international boundary and within Sonora, Mexico (fig. 1). Three major ephemeral streams—Rio Sonoyta and San Simon and Chukut Kuk Washes—meet in the study area. From its headwaters at the southern boundary of the study area, the Rio Sonoyta flows northwestward and is joined by the southward-flowing San Simon Wash and southwestward-flowing Chukut Kuk Wash. The stream system forms the gently sloping valley floor, which is bounded on the east by the La Lesna Mountains (Sierra de la Alesna in Sonora), Sierra del Cobota, and Sierra del Cobre; on the south by a surface-water and ground-water divide; and on the west by Cerros Manteca and San Juan de Ulua and Sierra de la Nariz. To the northwest between Sierra de la Nariz and the Mesquite Mountains is another ground-water divide. The Mesquite Mountains and the low hills north of Papago Farms form the northern boundary of the study area. The mountains of the study area generally are at altitudes of 2,500 to 4,200 ft above the National Geodetic Vertical Datum (NGVD) of 1929, and peaks in the Sierra del Cobre reach altitudes of as much as 4,500 ft. The altitude of the valley floor ranges from 1,600 to 2,200 ft.

Previous Investigations

Geologic, geophysical, and hydrologic studies by several investigators were helpful in evaluating the geohydrology and ground-water resources in the study area. Bryan (1925), in a reconnaissance report of the Papago Indian Reservation and west to the Colorado River, described the general geography, geology, and hydrology of the region. A regional appraisal of the geohydrology of the Papago Indian Reservation is shown on maps by Heindl and Cosner (1961), Heindl and others (1962), Hollett (1981b), and Hollett and Garrett (1984). Discussions concerning the geohydrology in and around Papago Farms can be found in Heindl (1976), Norvelle and others (1979), and Hollett (1981a).

The surface geology and structure in the Papago Farms-Great Plain area is shown as part of the regional appraisals by Wilson and others (1969), Cooley (1977), and Haxel and others (1980, 1981). Details on geology and structure of the Papago Farms area in the Kom Vo and La Lesna 15-minute quadrangles were obtained from Gordon Haxel and Richard Leveque (U.S. Geological Survey, written commun., 1979-81). North of the international boundary, the thickness and distribution of the deposits were determined on the basis of gravity studies (Greenes and others, 1979; Greenes, 1980) supported by residual aeromagnetic data (U.S. Geological Survey, 1980), drill-hole data (Heindl and Cosner, 1961); and vertical-electrical soundings (Turner and Associates, written commun., 1957). South of the international boundary, the distribution and thickness of basin-fill deposits were estimated from preliminary, low-level, aeromagnetic data (IFEX International, S. A., Hermosillo, Sonora, written commun.,

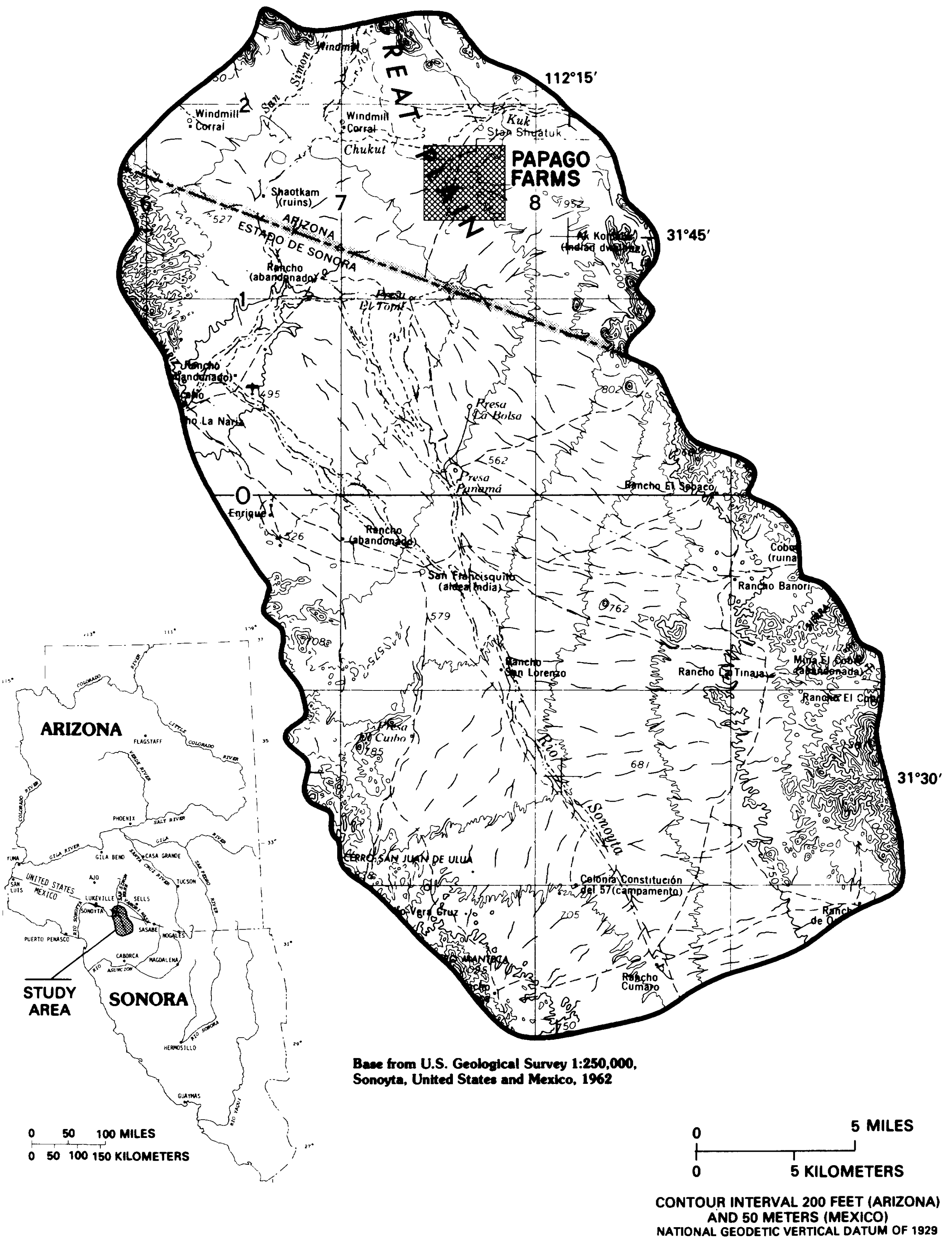


Figure 1. Area of report and location of Papago Farms.

1981) and geophysical and drillers' logs (Secretaria de Agricultura y Recursos Hidraulicos, Hermosillo and Sonoyta, Sonora, written commun., 1980, 1981). Surface geology encompassing the upper Rio Sonoyta area is shown in Merriam (1972) and Consejo de Recursos Naturales (1967). Regional geophysical maps that include the Papago Farms-Great Plain area are in Hargan (1978), U.S. Geological Survey (1980), International Exploration, Inc. (written commun., 1979), Oppenheimer and Sumner (1981), and Lysonski and others (1981). Geothermal potential at Papago Farms was evaluated by Stone (1980). Basic quality-of-water and water-level data for the Papago Farms-Great Plain area are published in Heindl and Cosner (1961), Heindl and others (1962), Hollett (1981b), and Hollett and Garrett (1983). Surface-water data for San Simon and Vamori Washes are published in the U.S. Geological Survey Water Resources Data for Arizona (1972-74a, b; 1976-83).

Methods of Investigation

The surface geology of the study area was compiled from published reports and maps, Landsat and SKYLAB infrared-imagery analyses, and low-level black and white stereo-imagery analyses. Reconnaissance geologic mapping was done where existing data were too generalized. Haxel and others (1980; 1981) identified bedrock units near Papago Farms. The subsurface structure and stratigraphy of the Papago Farms-Great Plain area was determined from geophysical surface and borehole surveys, drillers' logs, and drill cuttings. Water-level and chemical quality-of-water data were taken from Heindl and Cosner (1961).

Compiled information and data were used to develop a preliminary conceptual model of the geohydrologic system in the Papago Farms-Great Plain area. On the basis of information from the conceptual model, areas of sparse or missing data were identified, and a program of additional fieldwork, which included well inventory, water sampling, geophysical surveys, and well drilling, was initiated. Ground-water pumpage was estimated from irrigated acreage and crop-consumptive use or from irrigation-well engine-hour records. Transmissivity values were extrapolated to various parts of the basin on the basis of a few short-term well tests at or near Papago Farms (Heindl, 1976; Norvelle and others, 1979; this study). To a limited extent, a specific capacity and transmissivity relation for the tested wells was used for estimating transmissivity at untested wells. Only widely scattered specific-capacity data were available for the upper Rio Sonoyta area.

Fieldwork in the early stages of the project was directed toward a comprehensive well inventory and water-sampling program in order to define the steady-state conditions of the geohydrologic system in the Papago Farms-Great Plain area. The fieldwork was done before ground-water withdrawal at Papago Farms was reactivated after more than 15 years of dormancy. In addition to a complete inventory of existing wells in the Papago Farms-Great Plain area, six observation wells were drilled 1 to 4 mi outside the perimeter of Papago Farms. The wells were used to determine the water level, subsurface stratigraphy, aquifer transmissivity, and chemical quality of the ground water. From January to September 1981, water levels in most wells in the Papago Farms-Great Plain area were measured at least semiannually. Continuous water-level measurements were made at selected sites in the Papago Farms area during part of 1979 and 1980.

Fieldwork in the upper Rio Sonoyta area consisted of two trips to measure water levels and collect water samples in selected wells. Water-level, discharge, and depth information for many wells was made available for use in the study by the personnel of the Secretaria de Agricultura y Recursos Hidraulicos (Secretariat of Agriculture and Hydraulic Resources) in Sonoyta and Hermosillo, Sonora, Mexico.

Well-Numbering and Naming System

The well numbers used for wells in the upper Rio Sonoyta area (fig. 2) are in accordance with the system established by the Secretaria de Agricultura y Recursos Hidraulicos Residencia de Geohidrologia y de Zonas Aridas en el Estado de Sonora, Zona Norte (Secretariat of Agriculture and Hydraulic Resources, Department of Geohydrology and Arid Zones in the State of Sonora, Northern Zone).

Well names for wells located in the Papago Farms-Great Plain area (fig. 2) are in accordance with those established by the U.S. Bureau of Indian Affairs and the Papago Tribe of Arizona and used by Heindl and Cosner (1961). In many cases, a well may be identified by a location name and a sequential number in a drilling program. For instance, the Stoa Tontk well also is identified as DW-31.

GEOLOGY AND ITS RELATION TO THE HYDROLOGIC SYSTEM

The Papago Farms-Great Plain and upper Rio Sonoyta study area includes two principal topographic features—the low, jagged, basin-bounding mountains and the broad, intermontane desert floor. The La Lesna, La Nariz, and Mesquite Mountains and some unnamed mountains in the northern half of the study area are mainly the exposed parts of tilted fault blocks of Tertiary volcanic rocks (fig. 3). The mountains in the southern half of the study area are mainly pre-Tertiary undifferentiated metamorphic and granitic rocks that are capped in many places by faulted and tilted volcanic rocks. The desert floor is underlain by poorly to moderately consolidated basin-fill deposits.

Geologic Units and Their Water-Bearing Properties

The volcanic, metamorphic, and granitic rocks and thin interbedded sedimentary rocks that surround the study area store and transmit smaller quantities of water than the more porous and hydraulically conductive basin fill. The metamorphic and granitic rocks generally have the lowest hydraulic conductivity; the hydraulic conductivity of the volcanic rocks is highly variable and dependent on the amount of interflow brecciation and on the development of interconnecting fractures. Although the surrounding rock units do not store or transmit large quantities of water to wells, they confine and, in some areas, structurally control the flow of ground water in the basin fill.

In the study area, the uncemented to moderately cemented basin fill is more than 8,000 ft thick (fig. 3). The sedimentary deposits range in age from Tertiary to Quaternary; however, no further attempt was made to subdivide these deposits because of the sparsity of deep drill-hole data. The descriptions of basin fill, rocks of the surrounding mountains, buried pediments, and units that underlie the basin fill are presented on the basis of their water-bearing properties.

Granitic, Metamorphic, and Volcanic Rocks

The oldest rocks exposed in the surrounding mountains consist of granite and gneiss of Precambrian age (Merriam, 1972). The granite and gneiss presumably form the basement complex but are exposed only in the southern part of the upper Rio Sonoyta area. A second, younger group of granites crops out as isolated patches within even younger rocks or as isolated hills. This younger granite is plutonic and is either a part of a Middle to Late Jurassic magmatic episode or a Late Cretaceous or Tertiary episode during the Larimide orogeny (Haxel and others, 1980, 1981). The younger granite is exposed in the Kupk Hills, in the La Lesna Mountains at the international boundary, and in the hills south of Cerro La Nariz (fig. 3).

Undifferentiated metamorphic rocks of unknown origin crop out in the Sierra del Cobre on the east. Westward dips predominate, as observed by Haxel and others (1980) for similar rocks of the southern Papago terrane. The metamorphic and granitic rocks are mapped as one unit of pre-Tertiary age on the basis of similar water-bearing properties (fig. 3). The unit may contain small amounts of water along fractures and in weathered zones but probably would not provide a dependable water supply. No known wells have been developed in this unit in the area.

Undifferentiated volcanic flows and pyroclastic rocks cap the Precambrian rocks of the Sierra de la Alesna, Sierra del Cobota, and parts of the Sierra del Cobre. No known wells or springs are in these rocks; however, where interlayered conglomerate and breccia or flows are highly fractured, the rocks may store and transmit small amounts of water.

The Sierra de la Nariz and La Lesna Mountains are made up almost entirely of dark-gray to reddish-brown coarsely porphyritic latite and andesite flows and interflow breccias, bedded mudstones, and sandy beds. These rocks form rugged, steep, cobbly mountain fronts and intricately patterned dip slopes. The latite and andesite unit also has a high proportion of brecciated or fractured to massive rock. Interflow breccias are thick, rough, and jagged; they resemble giant cinders, particularly on the steep faces of tilted mountain blocks. The interflow breccias and fracture zones may store and transmit large quantities of water.

A few wells in the area tap the faulted latite and andesite unit, but little is known about sustained yields. On the basis of information from well owners in the area, wells that tap this unit may produce yields that exceed 50 gal/min. Well 10-01 (fig. 2), secluded in the main valley of Sierra de la Nariz, produces about 100 gal/min of water from rock and a thin layer of saturated, surficial alluvial deposits.

A unit of banded rhyolite flows and tuffs is common in the area and makes up most of the Mesquite Mountains and low hills north of Papago Farms. This unit caps many of the higher mountain ranges in the southern part of the area (fig. 3). The unit interfingers and lies conformably on the latite and andesite unit and is overlain with a pronounced angular unconformity by the olivine basalt and basaltic andesite unit. The tabular banded rhyolite flows and tuffs are faulted, generally in nearly parallel bands, and tilted to the northeast. The tilt of the unit is readily recognizable in outcrop. In most cases the rocks of this unit lie above the regional water table, and any water that might be developed would be localized accumulations in intensely fractured and brecciated zones.

The olivine basalt and basaltic andesite rocks are generally flat-lying to gently dipping dark-gray to black flows that cap the Mesquite Mountains and occur as isolated knolls and ridges protruding from the desert floor. The outcrops are thin, deeply eroded, and widely scattered throughout the study area. The rocks of this unit form the prominent black cliffs and brown ridges along the slopes of many of the ranges and hills.

The high degree of vesicularity and interflow brecciation of the olivine basalt and basaltic andesite unit may indicate moderate to good water-bearing properties; however, the unit is too widely scattered and too deeply eroded to store significant amounts of water. Only small amounts of water infiltrating the rock unit may be stored; most would probably pass through to a lower bedrock unit or the adjacent basin-fill deposits.

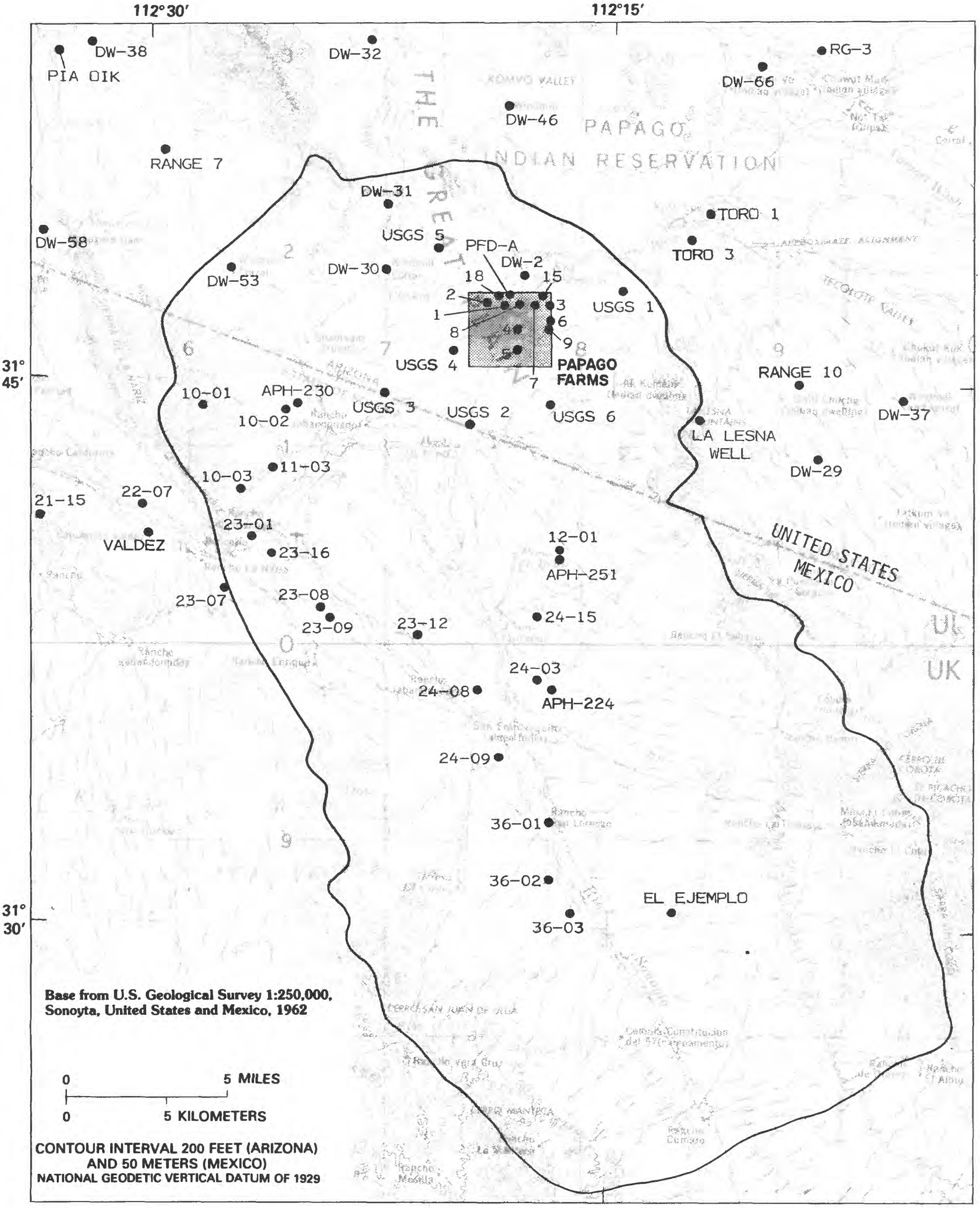


Figure 2. Well locations in the Papago Farms-Great Plain and upper Rio Sonoyta study area.

Basin Fill

Basin fill is the sedimentary material that fills the basin between the mountains and hills and covers the pediments and lower slopes. Basin fill is a heterogeneous mixture of uncemented to moderately cemented clay and caliche; poorly to well-bedded gravel, sand, silt, and clay; and some evaporites. Basin fill was deposited as irregular overlapping and interfingering lenses of slope wash and alluvium in the mountain valleys and along the mountain slopes and grades laterally to alluvial-fan, deltaic, and stream deposits over the pediments and near the buried pediment edges along the basin margin. These basin-margin sediments interfinger with massive beds of the basin-center lakebed-clay deposits. Moderately to well-consolidated conglomerates in the basin fill generally lie below the unconsolidated deposits. Conglomerates have been encountered in wells at Papago Farms and along Rio Sonoyta at depths that range from about 800 to 1,200 ft. Geophysical data indicate that the depth to the conglomerate increases toward the basin center and that the conglomerate is below the lakebed-clay deposits. The basin fill is at least 8,000 ft thick at the international boundary and thins to extinction along the mountain fronts.

Lateral and vertical distribution of the various sedimentary deposits governs the water-yielding characteristics of the basin fill. The deposits can be grouped into four major categories: (1) alluvial-fan deposits, (2) stream-channel deposits, (3) deltaic deposits, and (4) lakebed-clay deposits. Figure 4 shows the approximate distribution of these units at a depth of 500 ft.

Alluvial-fan deposits

An alluvial fan is a segment of a cone of unconsolidated sedimentary material that radiates downslope from a point where a single stream or wash leaves a mountain area. Where more than one stream drains a mountain, a series of fans may coalesce along the mountain front to form a piedmont slope. As a result of erosion of the surrounding mountains in the study area, a mixture of boulders, cobbles, sand, and silt grades as large wedges and lenses of material away from the mountain slope to mainly gravel, sand, silt, and clay. The wedge of material thickens toward the basin center and interfingers with deltaic, stream-channel, and lakebed-clay deposits. As erosion of the mountains continues, the size of the mountains decreases and the depth and expanse of the basin fill increases.

EXPLANATION

12-01 ● **WELL—Identifier, 12-01, is well number or well name**

——— **BOUNDARY OF STUDY AREA**

Figure 2. Continued.

Small-scale cut-and-fill structures are common within the bedded alluvial-fan deposits. The structures represent small stream-channel deposits entrenched or braided on ancient fan surfaces. The deposits are coarser and more permeable than typical fan sediments deposited by sheetflow. Fan sediments typically are a poorly sorted bedded mixture of gravel, sand, and silt and contain a high proportion of clay. The cut-and-fill deposits are better sorted and contain fewer clay-size particles (Reineck and Singh, 1975, p. 256).

Coarser cut-and-fill deposits consist of lenses of gravelly sand between thick layers of gravelly, sandy, silty, clay lenses and can be identified in well cuttings and well logs. The coarser layers are thicker and more abundant near the apex of the fan at the basin margins and decrease in thickness and in median grain size toward the basin center.

Water yield to wells that tap the alluvial-fan deposits is highly variable. Yield is controlled primarily by thickness and extent of the deposits, number of cut-and-fill beds encountered, and the total thickness of water-yielding sediments penetrated by the wells. A well in the thin sediments overlying the pediments may yield less than 50 gal/min of water (Hollett, 1981a); however, properly designed and constructed wells that tap more than 200 ft of alluvial-fan material with a moderate amount of interbedded cut-and-fill structure may yield more than 1,500 gal/min of water.

Stream-channel deposits

A stream-channel deposit is created by high-velocity streamflow. Boulders, gravel, and sand dominate because silts and clays have been removed. Hydrogeologic characteristics of stream-channel deposits are similar to cut-and-fill structures of the alluvial-fan deposits.

Borehole and geophysical evidence in the vicinity of Papago Farms indicates that an ancient buried channel of lag gravel and sand trends eastward from Papago Farms (fig. 4). These deposits interfinger with extensive alluvial-fan deposits and are buried by the flood plain. Similar sediment probably exists beneath the reach of Rio Sonoyta as it exits the study area through a bedrock narrows just south of Cerro La Nariz. On the basis of data for some wells that tap stream-channel deposits, well yields greater than 1,800 gal/min may be common, and specific capacities may range from 20 to 50 (gal/min)/ft of drawdown.

Deltaic deposits

A delta is an accumulation of sediment deposited at the mouth of a river as a consequence of a reduction in streamflow velocity and a release of suspended sediment as the moving stream enters a still body of water. The delta is built as a prograding wedge of sediment that is characteristically a coarsening-upward sequence of clay, silt, sand, and

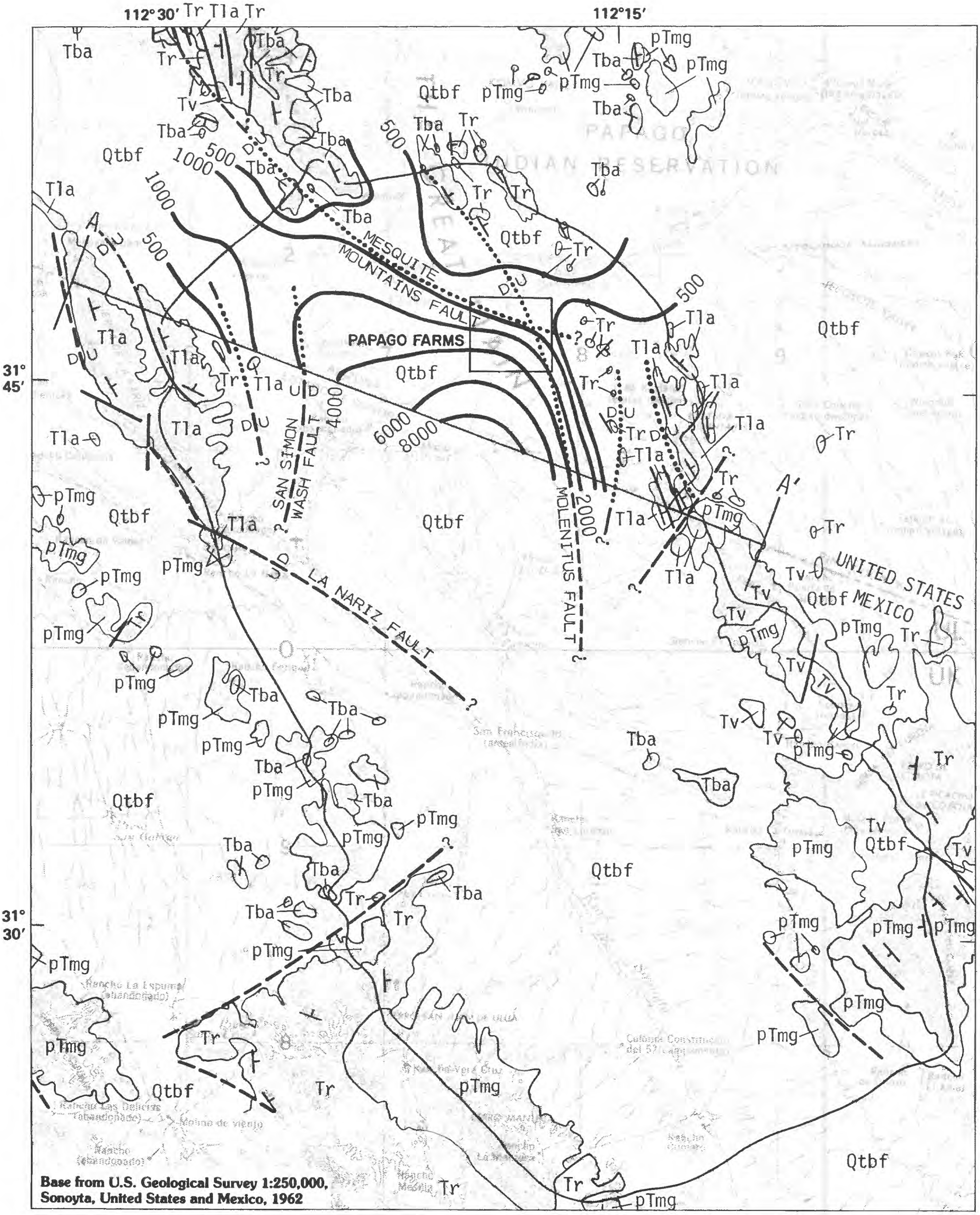


Figure 3. Reconnaissance geology, structure, and depth to bedrock in the Papago Farms-Great Plain and upper Rio Sonoyta study area.

gravel (Pettijohn, 1975). Beneath Papago Farms, a number of coarsening-upward sequences have been stacked one upon another.

Deltaic deposits at Papago Farms are isolated to a small area adjacent to the intersection of the Mesquite Mountains and Molenitus faults (figs. 3, 4). The deposits are estimated to be about 800 ft thick basinward of the fault intersection, thinning and interfingering with thick clays in the basin center (fig. 4).

The water-yielding characteristics of the deltaic deposits appear to be controlled by the thickness and extent of moderately sorted fine- to medium-grained sand layers in the deltaic sequence. Wells that partially penetrate the deltaic deposits at Papago Farms yield water at significantly higher rates than wells that penetrate the basin-center lakebed-clay deposits or alluvial-fan deposits. Yields to wells that tap these deposits at Papago Farms have been measured at more than 3,000 gal/min with specific capacities of 30 to 50 (gal/min)/ft of drawdown.

Lakebed-clay deposits

Lakebed-clay deposits are commonly thick sequences of fine-bedded or varved silts and clays deposited in a calm

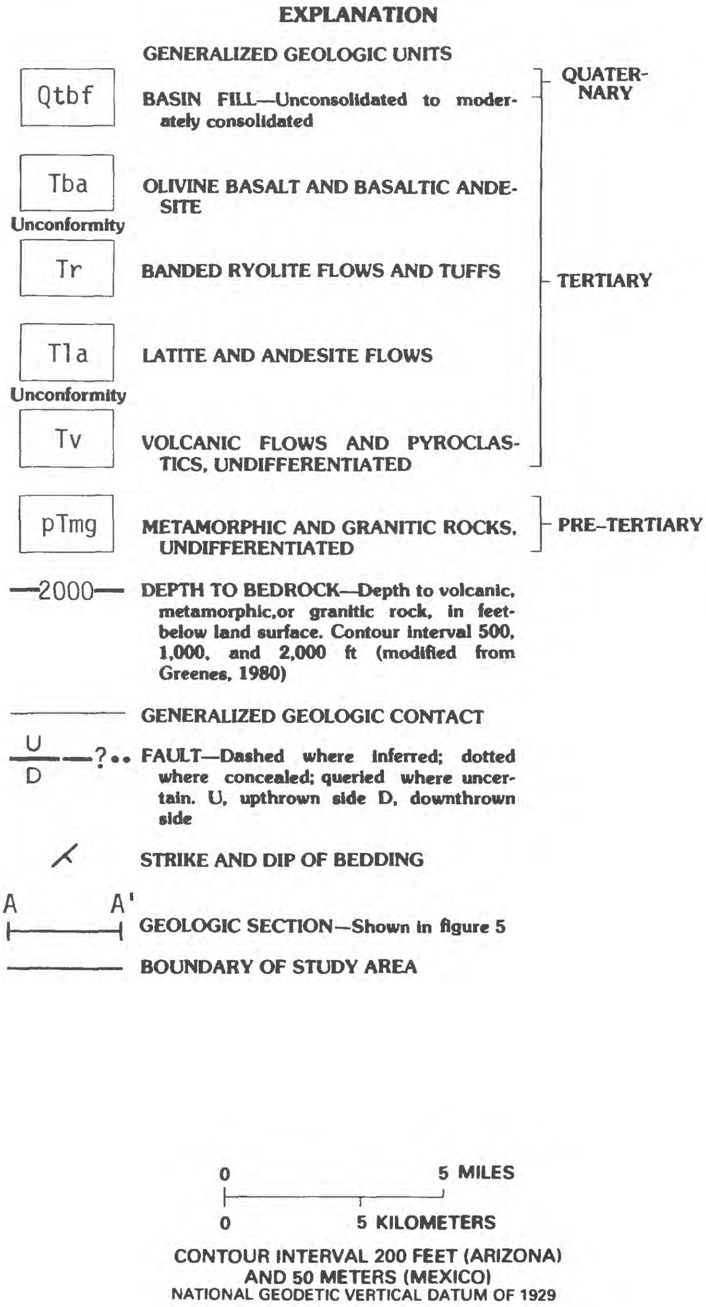


Figure 3. Continued.

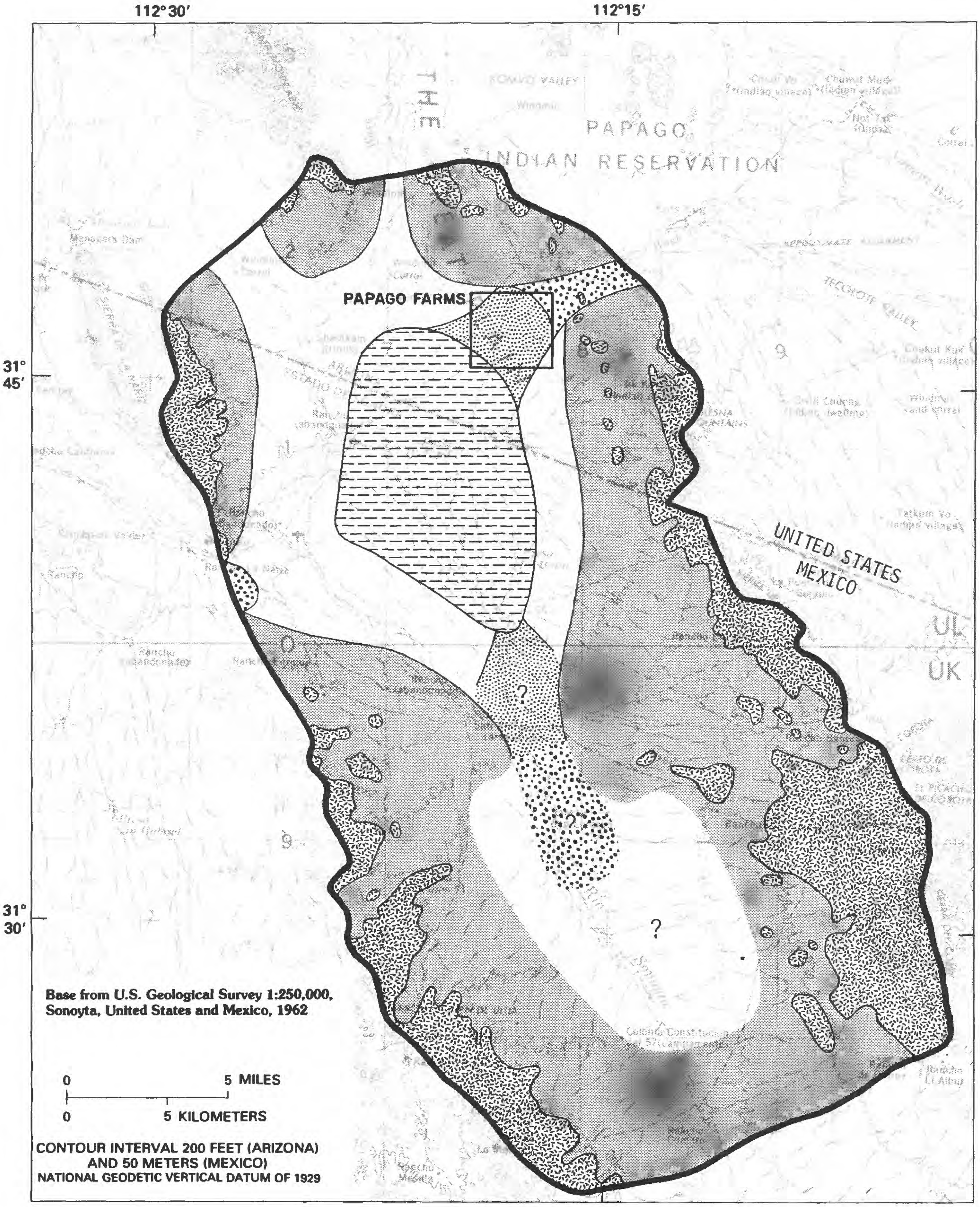


Figure 4. Distribution of sedimentary deposits in the basin-fill geologic unit.

lake or playa generally in an arid to semiarid environment. Lakebed-clay deposits are laterally and vertically persistent. The deposits usually are associated with varying amounts of evaporites. In the study area, thick sequences of dense sticky reddish-brown thinly bedded playa clays and thin stringers of fine silt occupy the center of the basin.

Analyses of sediments from wells in the basin center indicate that the lakebed-clay deposits extend to depths of more than 1,000 ft and are laterally extensive (fig. 4). The upper surface of the lakebed-clay deposits are covered by about 50-150 ft of sandy silt. Geophysical and geologic data indicate that the clay thins out completely toward the fault-block margins of the basin. The lakebed-clay deposits were probably laid down contemporaneously with the thick blankets of alluvial-fan deposits and with basin-center block subsidence; therefore, the two sedimentary units overlap and intertongue in a wide zone along the fault-block margins of the basin (fig. 4).

Wells that tap the basin-center lakebed-clay deposits generally yield less than 50 gal/min, and specific capacities are commonly less than 1 (gal/min)/ft of drawdown. Saturated clays, however, may yield moderate amounts of water to adjacent water-bearing units, but the yield is delayed by tens of years.

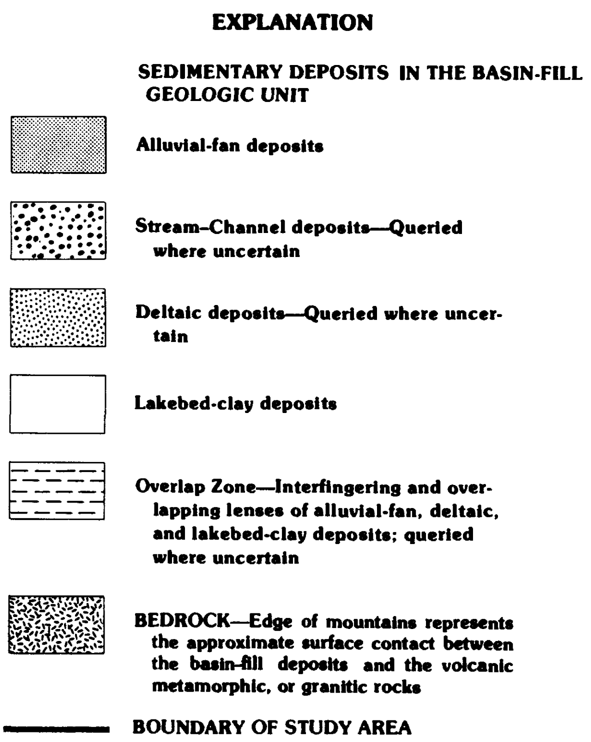


Figure 4. Continued.

Basin Structure

Geologic structure, which is the physical arrangement of the rock units, affects storage and movement of ground water. The deep, central basin of the study area is essentially a downdropped floor of rock surrounded on all sides by virtually impermeable steep mountain blocks that are faulted, tilted, eroded, and partially buried by basin fill. At least four major fault blocks surround the deep, central basin; the contacts between the blocks and the basin are represented by the Mesquite Mountains, Molenitus, San Simon Wash, and La Nariz faults (fig. 3).

The Mesquite Mountains fault trends along the southwest edge of the Mesquite Mountains and across the northern part of Papago Farms (fig. 3). Evidence of this fault, which was first noted by Cooley (1977), is based on displacement of exposed bedrock. Analyses of geophysical data from surveys by Greenes and others (1979), Greenes (1980), and U.S. Geological Survey (1980) were used to confirm the fault location. Wells at Papago Farms penetrate the bedrock on the upthrown side of the fault at about 600 ft below the land surface. Vertical offset across the fault is abrupt and may be as much as 6,000 ft.

The Molenitus fault trends south-southeast from the hills north of the Papago Farms and south along the foot of the La Lesna Mountains and intersects the Mesquite Mountains fault (fig. 3). As along the Mesquite Mountains fault, the vertical offset of the Molenitus fault is also abrupt and may be as much as 6,000 ft. The existence of the Mesquite Mountains and Molenitus faults is further reinforced by a geothermal investigation by Stone (1980). Stone (1980) concluded that a low-temperature geothermal anomaly that is centered in the north-central area of Papago Farms may be caused by warm ground-water that moves up the intersecting fault zones.

The San Simon Wash fault is along the east side of the Sierra de la Nariz and generally parallels the Molenitus fault. Vertical offset along the San Simon Wash fault is less abrupt than the vertical offset of the Molenitus or Mesquite Mountains faults and occurs as a series of slumped bedrock blocks. A geologic cross section and profiled aeromagnetic and gravity data along the international boundary emphasize the relation of basin-bounding rock to the basin fill and the degree of fault offset (fig. 5).

Less is known about the La Nariz fault at the south end of the Sierra de la Nariz (fig. 3). On the basis of preliminary, low-level aeromagnetic data (IFEX International, S. A., Hermosillo, written commun., 1981), the exposed trend of the La Nariz fault extends to form the south edge of the basin. The vertical offset may be more than 2,000 ft and is similar to the stepped-block structure of the San Simon Wash fault.

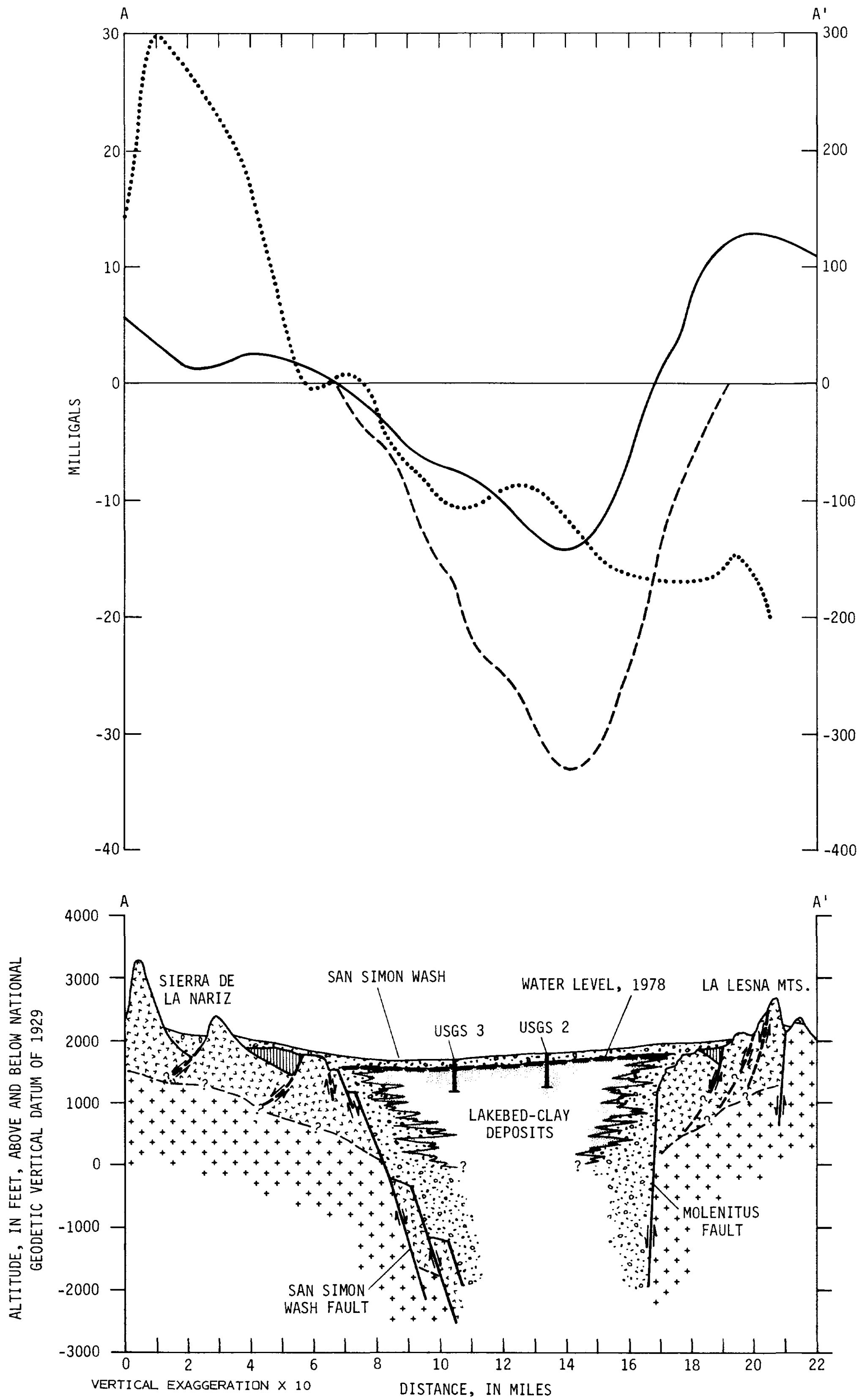


Figure 5. Gravity and magnetic profiles for geologic cross section A-A' along the international boundary.

WATER RESOURCES

Surface Water

Papago Farms-Great Plain and upper Rio Sonoyta basin is the confluence of three surface-water drainage systems: (1) San Simon Wash and the Vamori Wash system, (2) Chukut Kuk Wash, and (3) upper Rio Sonoyta (fig. 6). Main drainageways have many small braided channels that are poorly defined and that are distributary in places. The flood plain is broad and flat, and riparian vegetation has overgrown much of the channel and flood plains along the major streams. The capacity of the normally dry channels to convey runoff is small. Runoff commonly overtops the 3- to 5-foot-high banks, covers wide areas of the adjacent flood plains, and coalesces to form ponds. Ponds and muddy areas remain for many days following runoff. Streamflow is the result of local summer thunderstorms and regional winter storms. Precipitation averages 5 to 8 in./yr on the desert floor (Sellers and Hill, 1974) and is estimated to be 10 to 15 in./yr in the Sierra del Cobre. Precipitation and runoff are highly variable both in time and space.

EXPLANATION

TOTAL MAGNETIC INTENSITY—U.S. Geological Survey (1980)

RESIDUAL GRAVITY ANOMALY—D. Klein, U.S. Geological Survey (written commun., 1981)

SECOND—ORDER RESIDUAL GRAVITY ANOMALY—Greenes (1980)

GENERALIZED GEOLOGIC UNITS

Basin fill—Unconsolidated to moderately consolidated sediment. Includes lakebed-clay deposits.

Banded rhyolite flows and tuffs

Latite and andesite flows

Pre-Tertiary metamorphic and granitic rocks, undifferentiated

—?— GENERALIZED GEOLOGIC CONTACT—Queried where uncertain

FAULT—Arrow indicates movement of fault block

USGS 3 WELL—Identifier, USGS 3, is well name

Figure 5. Continued.

Streamflow data and water samples from two gaging stations north of the study area—Vamori Wash at Kom Vo (Santa Cruz village) and San Simon Wash near Pisinimo (fig. 6)—were used to estimate streamflow quantity, chemical quality, and sediment inflow to the Papago Farms-Great Plain area. The combined San Simon-Vamori Wash watershed supplies about 80 percent of the runoff to the study area. The remaining 20 percent of runoff is contributed by ungaged flow from the Chukut Kuk watershed and the area downstream from the gaging stations for the Vamori and San Simon Washes.

Annual unit runoff was calculated to be 0.09 in. or 0.007 $(ft^3/s)/mi^2$ for the two gaged watersheds. Because the physiographic and precipitation characteristics are similar for the entire watershed upstream from the outflow point of the study area, this unit runoff is assumed for the entire watershed. Thus, the estimated annual amount of surface inflow to the study area is 11,000 acre-ft from the 2,350-square-mile watershed. Net runoff from the drainage area within the 490-square-mile study area is estimated to be 3,000 acre-ft/yr, and the estimated amount of annual surface outflow from the study area in the Rio Sonoyta south of Cerro La Nariz is 14,000 acre-ft/yr.

The amount of variability of runoff in Vamori and San Simon Washes is shown by the mass curve for the combined daily flow of the two gaging stations (fig. 7). Because the mass curve represents a graphical accumulation of the combined daily amounts of flow, the stepped appearance and different size of steps along the curve indicate that runoff is highly variable. Runoff upstream from the study area is characterized by long periods of no flow and occasional periods of flow. Nearly one-third of the total flow for the 8-year period of record occurred during a 3-month period in the 1976 water year. During the period from mid-1973 to mid-1976, the average daily flow was only half the average daily flow for the 8-year period of record.

Duration of streamflow in Vamori and San Simon Washes is readily apparent from flow-duration curves for the combined, gaged tributary (fig. 8). Flow-duration curves for Vamori and San Simon Washes indicate that the median number of days per year of no flow at the gaging stations is about 310. Flow duration for the high and low years of combined flow are plotted on either side of the average flow-duration curve to indicate the range in flow possible from one year to the next. Extremes in volume of runoff from one water year to the next are indicated on the mass curve (fig. 7). About 85 percent of the time, the larger wash channels have no flow.

Although large amounts of water occasionally flow into the study area, diversion and storage in reservoirs may not be feasible because of high losses owing to evaporation. Kohler and others (1959) estimated average annual lake-evaporation rates in the study area to be more than 6 ft/yr. Thus, if the average water inflow of 12,000 acre-ft/yr were

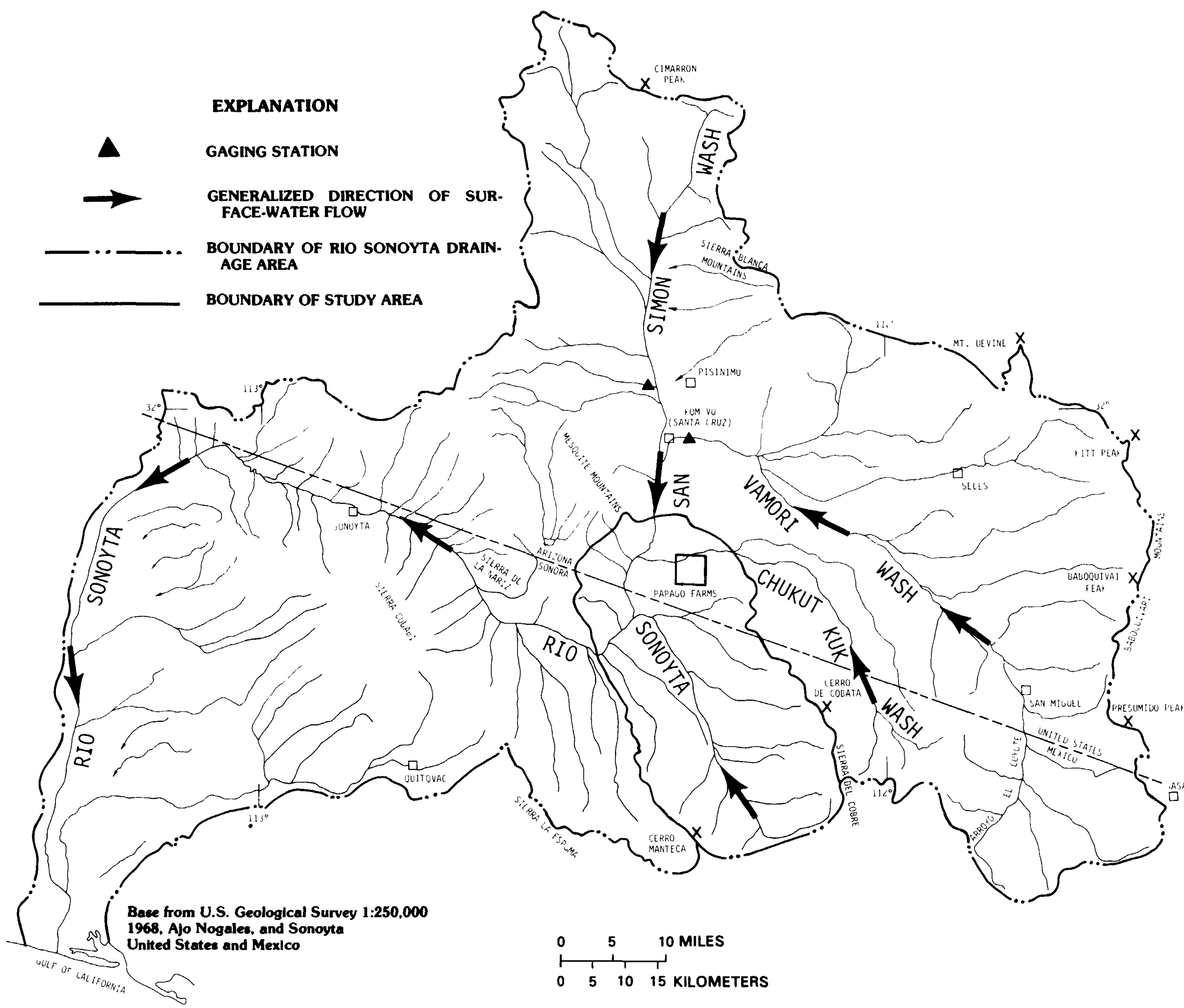


Figure 6. Watersheds and surface-drainage patterns for the Vamori, San Simon, and Chukut Kuk Washes and Rio Sonoyta.

stored in reservoirs, a large part of it would be lost to evaporation.

Near Presa El Topil (fig. 1), some attempt was made to divert runoff for irrigation use; however, many of the farms in the study area that used runoff for irrigation are now abandoned or have converted to the use of ground water for irrigation. Diversion of runoff is not considered a significant potential source for irrigation. Some runoff, however, is diverted to small catchment tanks for livestock use. The tanks are dry much of the time, and the primary water supply for livestock is the many scattered wells.

Chemical Constituents

Periodic sampling to determine chemical quality of water was done at the gaging stations at Vamori and San Simon Washes between 1977 and 1980. Chemical constituents in the water represent soluble products of eroded or weathered rock and soil. The water in the Vamori and San Simon Washes generally contains less than 167 mg/L (milligrams per liter) of dissolved solids and averages 114 mg/L dissolved solids (table 1). Calcium and bicarbonate are the principal ions in solution.

Suspended Sediment

Sediment data are vital in the design of surface-water storage or diversion structures, such as dams or canals. Flow that is retarded in such structures allows suspended sediment to settle and accumulate. Sediment accumulation could significantly reduce storage or transfer capacity and infiltration potential if the structure is designed for ground-water recharge.

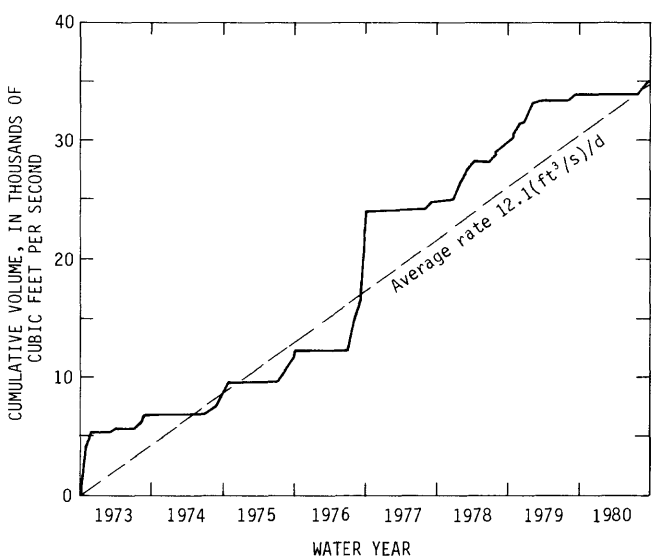


Figure 7. Mass curve of cumulative discharge, 1973-80, for the combined runoff for Vamori and San Simon Washes upstream from the Kom Vo gaging station (fig. 6).

The major streams entering the study area transport large amounts of suspended sediment. For the period of miscellaneous instantaneous measurements at the streamflow-gaging sites on the Vamori and San Simon Washes, 1977-80, sediment concentrations ranged from less than 700 mg/L to more than 100,000 mg/L. Typical values were between 1,000 and 50,000 mg/L for streamflow discharges of 10 to 200 ft^3/s. Streamflow that contains 10,000 mg/L of suspended sediment is 1 percent particulate solids.

Excessive range and scatter in sediment concentration versus streamflow precluded computation of an annual sediment load or sediment-rating curve. Sediment load, however, generally increases with increasing streamflow discharge. Data for Vamori and San Simon Washes indicate that the sediment load was about 200 to 2,000 tons/d for streamflow discharges of 50 ft^3/s and 3,000 to 50,000 tons/d for streamflow discharges of 500 ft^3/s. A large range in sediment load for the same streamflow discharge is a function of many environmental variables, such as vegetation cover and storm location, duration, and intensity.

Ground Water

Ground water is the mainstay of irrigation and public water supply in the study area. The ground water is ample in quantity but of variable chemical quality. Ground water is derived mainly from the basin fill; in contrast, ground water in the mountain areas is scarce or nonexistent.

Nearly all the recoverable ground water in the study area is in the unconsolidated and partly consolidated Tertiary and Quaternary basin-fill deposits. Where saturated, these deposits and a few buried latite and andesite flows along the margins of the basin form the aquifer. The aquifer is capable of yielding significant quantities of ground water to wells. Some ground water may occur in the rhyolitic and basaltic rocks of the area; however, the absence of springs and wells in this unit indicates that quantities of water are negligible.

Occurrence and Movement

Ground water occurs in the basin fill under unconfined or water-table conditions. The depth to water in wells ranges from about 150 ft in the center of the study area to about 500 ft near the southern boundary. Water levels in wells at Papago Farms range from 200 to 240 ft.

Altitudes of the water table are based on water levels measured in the Papago Farms-Great Plain area prior to reactivation of farming at Papago Farms and represent static conditions in late 1977 (fig. 9). Water levels in the upper Rio Sonoyta area reflect measurements made from 1978-80 (fig. 9).

Ground water moves in the direction of decreasing hydraulic head perpendicular to water-level contours and

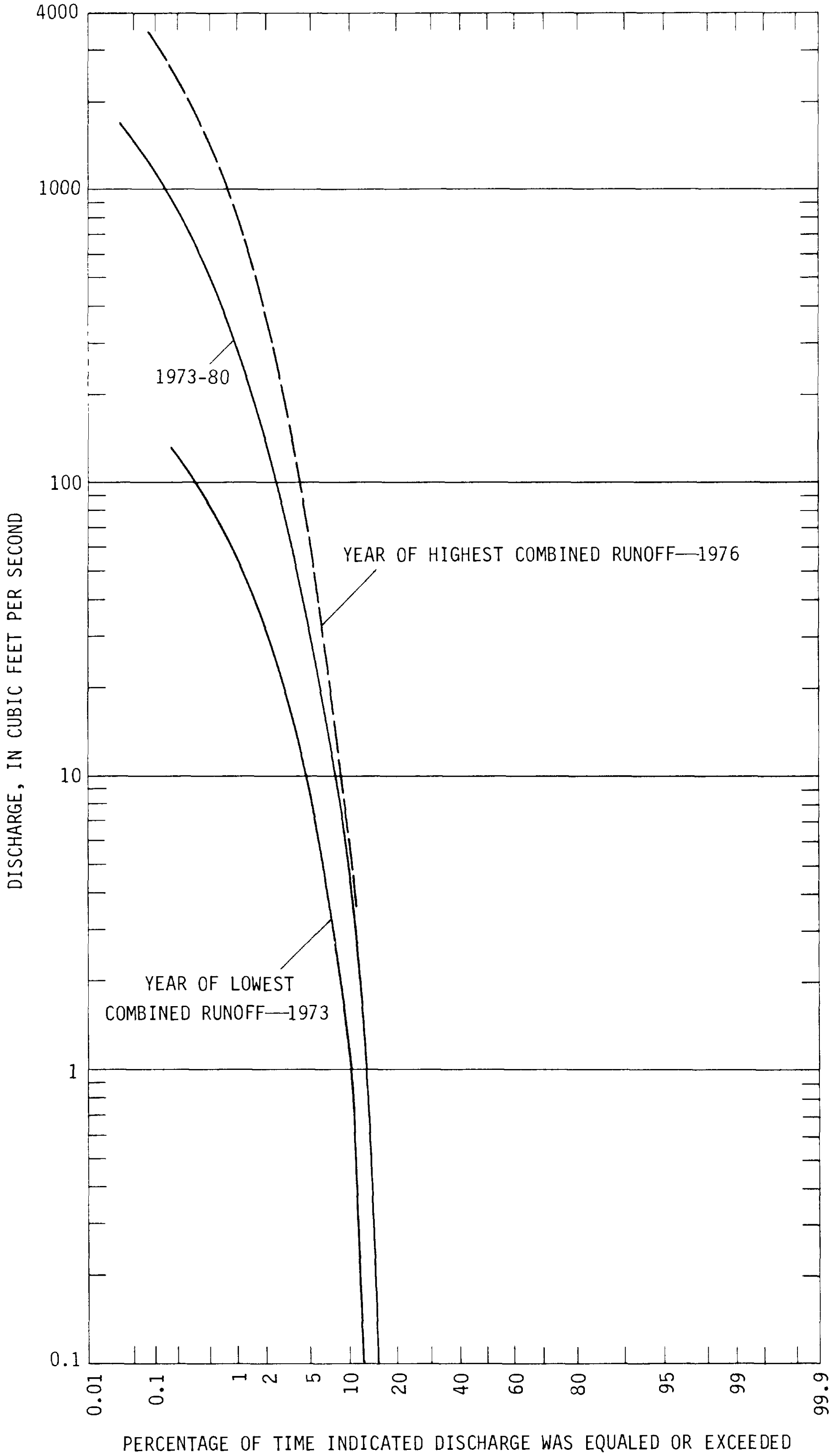


Figure 8. Flow-duration curves of combined daily flow for Vamori and San Simon Washes.

Table 1. Chemical constituents and physical properties of the water in San Simon and Vamori Washes, 1977-80

Constituent or property	San Simon Wash	Vamori Wash Range	Vamori Wash Mean	Vamori Wash Number of analyses
Instantaneous discharge (ft^3/s)--	--	13-458	141	8
Silica, dissolved (SiO_2)---------	6.8	6-16	11	8
Iron, total (Fe)-----------------	1.5	8-62	38	4
Manganese, total (Mn)------------	<.01	.26-2.2	1.2	4
Calcium, dissolved (Ca)----------	13	12-38	23	8
Magnesium, dissolved (Mg)--------	2.7	.1-5.4	3.6	8
Sodium, dissolved (Na)-----------	1.1	4-12	7.8	8
Potassium, dissolved (K)---------	7	4.4-14	9.2	8
Bicarbonate, dissolved (HCO_3)----	41.5	50-146	97	8
Sulfate, dissolved (SO_4)---------	9.1	1.7-9.1	5.8	8
Chloride, dissolved (Cl)---------	2.6	1-4.8	3.2	8
Fluoride, dissolved (F)----------	.1	.1-.8	.3	8
Nitrate and nitrite as N (NO_2+NO_3 as N)--------------	.01	.03-1.9	1.1	4
Phosphorus, dissolved (P)--------	--	.92-2.2	1.6	5
Dissolved solids, calculated-----	65	59-167	114	8
Hardness ($CaCO_3$)-----------------	44	30-120	72	8
Hardness, noncarbonate-----------	9	0-14	3	8
Dissolved oxygen-----------------	9.8	6.4-9.6	8	2
pH-------------------------------	--	7.2-9.3	7.9	6
Arsenic, total (As)--------------	--	.006-.011	.009	3
Barium, total (Ba)---------------	--	<.10-.60	.4	4
Cadmium, total (Cd)--------------	--	0-.008	.002	4
Chromium, total (Cr)-------------	--	.02-.06	.04	4
Cobalt, total (Co)---------------	--	.003-.03	.016	4
Copper, total (Cu)---------------	--	.016-.090	.058	4
Lead, total (Pb)-----------------	--	.005-.120	.066	4
Mercury, total (Hg)--------------	--	<.0001-.0003	.0002	4
Selenium, total (Se)-------------	--	0-.001	.0005	3
Silver, total (Ag)---------------	--	0	0	5
Zinc, total (Zn)-----------------	--	0	0	5

from areas of inflow to the outflow point. Water enters the study area beneath the San Simon and Chukut Kuk Washes and along the mountain fronts of the upper Rio Sonoyta area (fig. 9). Ground water moves through the basin fill and mostly around the low hydraulically conductive basin-center lakebed-clay deposits toward the outflow point of the basin beneath the Rio Sonoyta south of Cerro La Nariz. Between Kots Kug and Papago Farms, the gradient of the water table is about 20 ft/mi (fig. 9). Near Papago Farms, the gradient flattens to 3 ft/mi and gradually steepens to 10 ft/mi at the outflow point. The gradient of the water table is steepest near the mountain front of the Sierra del Cobre, where it is estimated to be more than 70 ft/mi.

Hydraulic Characteristics of the Aquifer

The hydraulic characteristics of an aquifer affect the rate at which water moves through the aquifer, the amount of water in storage, and the rate and areal extent of water-level declines caused by ground-water withdrawal. The hydraulic characteristics—saturated thickness, porosity, hydraulic conductivity, transmissivity, specific capacity, rate of movement, and specific yield—were estimated mainly from drill-hole, geophysical, and aquifer-test data.

Saturated thickness

The saturated thickness of the aquifer (fig. 10) is the difference between the altitude at the base of the aquifer (fig. 11) and the altitude of the water level (fig. 9). The base of the aquifer in the study area was determined mainly from geophysical data, supplemented by some drill-hole data. In the Papago Farms-Great Plain area, the base was calculated from gravity data (Greenes, 1980) and aeromagnetic data (U.S. Geological Survey, 1980). Drill-hole data near Papago Farms verified that the depths determined by the geophysical data were within 100 ft of actual depths for unconsolidated material less than about 1,000 ft thick. In the upper Rio Sonoyta area, the base of the aquifer is not as well known. The general shape, however, can be estimated on the basis of the distribution of the major subsurface fault blocks, which was interpreted from preliminary areomagnetic data (IFEX International, S. A., Hermosillo, written commun., 1981), and borehole-geophysical logs (Secretaria de Agricultura y Recursos Hidraulicos, Hermosillo, written commun., 1980).

The saturated thickness in the center of the basin exceeds 8,000 ft. Hydraulic properties of the saturated basin fill below about 1,500 ft, however, are not well known; therefore, for the purposes of this report, the base of the aquifer

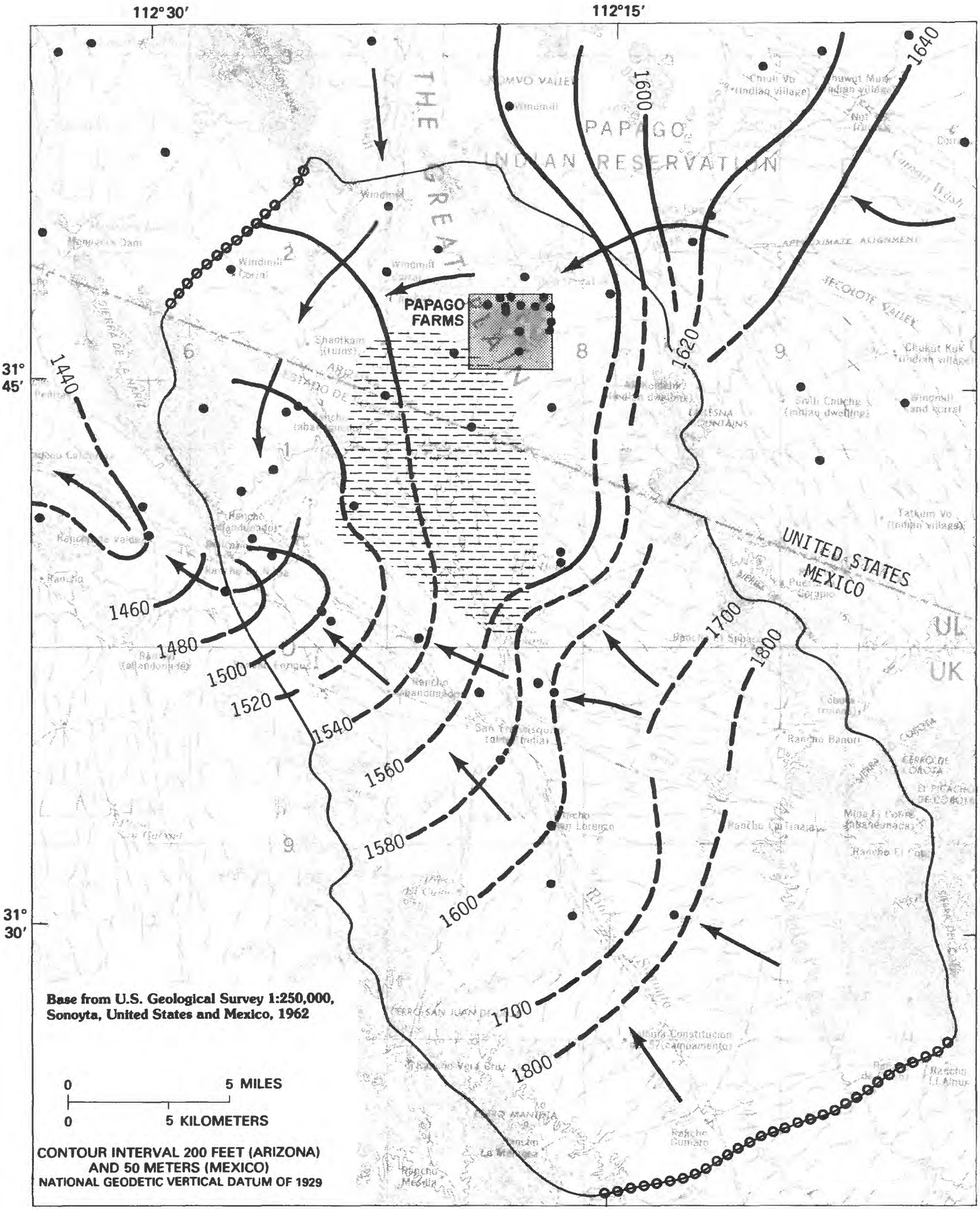


Figure 9. Configuration of the water table in the Papago Farms-Great Plain area, 1977, and the upper Rio Sonoyta area, 1978-80.

(fig. 11) has been set at an altitude of 500 ft above NGVD of 1929, which is about 200 ft below the deepest finished well in the area.

Properly constructed and developed wells outside the zone of basin-center lakebed-clay deposits that tap more than 300 ft of saturated basin fill in the upper 1,000 ft of the aquifer generally yield sufficient quantities of water for irrigation. Continuous water yields from such wells range from 500 to 3,000 gal/min with specific capacities of 10 to 50 (gal/min)/ft of drawdown.

Porosity, hydraulic conductivity, transmissivity, and specific capacity

Porosity of the sedimentary deposits is the ratio of the volume of pore spaces to the total volume of material. In general, rocks have a lower porosity than unconsolidated sediments, and well-sorted fine-grained sediments have a higher porosity than poorly sorted coarse-grained sediments. Water in the aquifer occurs almost entirely in the pore spaces between granular sedimentary particles. Hydraulic conductivity is the rate of flow of water through the interstices and depends primarily on the degree of connection of interstices. Well-sorted coarse-grained sediments normally store and yield more water than poorly sorted fine-grained sediments.

In the study area, in order of decreasing hydraulic conductivity, the sedimentary units are deltaic, stream-channel, alluvial-fan, and lakebed-clay deposits. The sedimentary units interfinger over wide areas and create a stratified environment. The stratification of sediments of differing hydraulic properties creates conditions in which horizontal hydraulic conductivities are typically higher than vertical hydraulic conductivities. Hydraulic conductivities are further reduced with depth as the sediments become more consolidated and also by precipitation of caliche in the pore spaces of all four units.

The transmissivity of an aquifer is defined as the rate of flow, in feet squared per day, at the prevailing kinematic viscosity through a cross section of aquifer having a width of 1 ft and height equal to a given thickness of the aquifer under a unit hydraulic gradient (Lohman, 1979). Transmissivity is equal to the sum of hydraulic conductivities across a 1-foot-wide saturated section of the aquifer perpendicular to the flow path.

Short-term aquifer and well tests made on several wells in the Papago Farms area provided estimates of transmissivity. Transmissivities of the aquifer ranged from about 100 to 40,000 ft^2/d. Harshbarger (Harshbarger and Associates, written commun., 1981) concluded that long-term aquifer tests from properly constructed and developed wells at Papago Farms would probably result in transmissivity values of about 27,000 ft^2/d.

Most wells in the study area partially penetrate the aquifer and are perforated or screened from the water table to the bottom of the well. Hydraulic conductivities, therefore, were estimated by dividing the transmissivity by the saturated thickness penetrated by the well. Hydraulic conductivities ranged from less than 1 to 80 ft/d. The values were within the range of calculated hydraulic conductivities for specific types of sedimentary material (Davis, 1969; Lohman, 1979, table 17).

Attempts were made to relate specific capacities to transmissivities for the wells tested, but results were poor. Transmissivities are roughly proportional to specific capacities; however, well losses owing to the different types of well construction, methods of development, and existing condition of wells in the study area have a significant effect on the range of specific capacities observed. Specific capacities for about 25 wells in the study area ranged from 0.1 to 60 (gal/min)/ft of drawdown. Although changes in specific capacity were not consistent with transmissivities, specific capacity was useful as a qualitative indicator of either high or low transmissivities for a particular part of the study area. The distribution of a specific capacity less than 7 (gal/min)/ft of drawdown was useful in delineating the extent of the basin-center lakebed-clay deposits.

EXPLANATION

—— 1560 — — WATER-LEVEL CONTOUR—Altitude of Water level prior to development in 1978 at Papago Farms. Altitude of water levels in upper Rio Sonoyta reflects measurements from 1978-80. Dashed where approximately located. Contour interval 20 and 100 feet. National Geodetic Vertical Datum of 1929

● WELL FOR WHICH DEPTH-TO-WATER DATA WERE AVAILABLE

→ GENERALIZED DIRECTION OF GROUND-WATER FLOW

APPROXIMATE EXTENT OF BASIN-CENTER LAKEBED-CLAY DEPOSITS

oooooooooooooo GROUND-WATER DIVIDE—Approximately located

BOUNDARY OF STUDY AREA

Figure 9. Continued.

Rate of movement

The ground water in the study area moves at rates that range from a fraction of a foot to hundreds of feet per year depending on the porosity, hydraulic conductivity, and hydraulic gradient. Except under special circumstances, such as flow in large fractures and cavities in consolidated rock and in highly conductive material with unusually steep

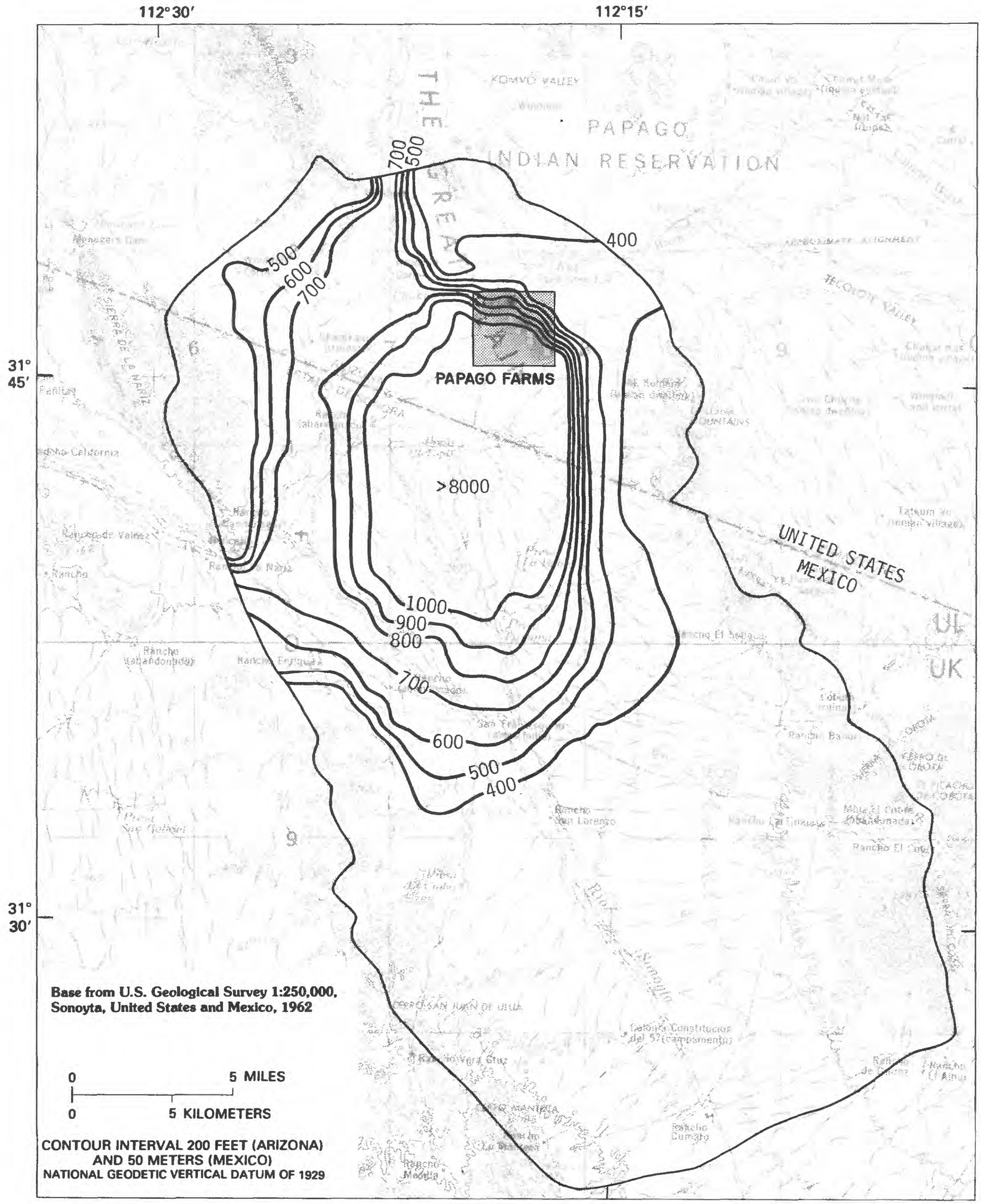


Figure 10. Saturated thickness of the basin fill.

hydraulic gradients as is found near pumping wells, the rate of ground-water flow or underflow can be estimated by the equation

$$v = \frac{KI}{n}, \qquad (1)$$

where

v = rate of movement, in feet per day;
K = hydraulic conductivity, in feet per day;
I = hydraulic gradient, (dimensionless); and
n = porosity, in percent.

For example, the velocity of ground-water flow through basin-center lakebed-clay deposits that have a porosity of about 40 percent, hydraulic conductivity of 0.1 ft/d, and a hydraulic gradient of 3 ft/mi is estimated to be 0.05 ft/yr. In contrast, the velocity of flow through the deltaic deposits beneath the Papago Farms at the same hydraulic gradient but a higher hydraulic conductivity of 80 ft/d may be 55 ft/yr. At the outflow point in the stream-channel deposits, where the gradient is steeper and the hydraulic conductivity is higher, velocities are estimated to be about 160 ft/yr.

Specific yield

The specific yield of an aquifer is the ratio of the volume of water the aquifer will yield by gravity to the volume of the aquifer expressed as a percentage. For the basin fill, the principal factors that control specific yield are size and sorting of the sediment grains as well as the time allowed to fully drain the water from the pore spaces of the sediments. Fine-grained poorly sorted material will yield less water and drain at a slower rate than coarse-grained well-sorted material. Because of the slow drainage of water from fine-grained material, a long-term (months) aquifer test would be needed to determine the specific yield of the types of sediments in the study area.

Estimates of specific yield, however, were derived on the basis of published aquifer tests in similar materials (Johnson, 1967). Estimated specific yield ranged from less than 4 percent in the basin-center lakebed-clay deposits to more than 15 percent in parts of the alluvial-fan, deltaic, and stream-channel deposits. The estimates compare well with estimated values for deposits beneath the Papago Farms by Heindl (1976) and Harshbarger (written commun., 1981). A basinwide average of 10 percent is considered reasonable.

EXPLANATION

— 600 — LINE OF EQUAL SATURATED THICKNESS OF THE BASIN FILL—Interval 100 ft

——— BOUNDARY OF STUDY AREA

Figure 10. Continued.

Chemical Quality

The chemical analyses of the ground water from 46 wells in and adjacent to the study area indicate a wide range of concentrations for dissolved constituents (table 2). On the basis of the major-ion chemistry of water from these wells, one chemical type was prevalent—a sodium bicarbonate water. The classification of water is illustrated in a trilinear or Piper (1944) diagram (fig. 12). Most of the values for the well water used for irrigation fall in a tight grouping of points in the sodium bicarbonate section of the diagram. A noticeable trend in the distribution of points indicates the ground water becomes more concentrated in sodium and bicarbonate downgradient from the mountain fronts toward the basin center.

Trends in ground-water chemistry as noted on the trilinear diagram are further illustrated in figure 13. The chemical-quality diagrams illustrate the different amounts of cations and anions in the water. The shape of the diagrams and the ratio of sodium to magnesium plus calcium, particularly in the upper Rio Sonoyta area, change as the ground water moves downgradient from the mountain fronts through the basin fill and toward the outflow point (fig. 13). The sodium to calcium plus magnesium ratio is an important consideration because of ion-exchange reactions in the soil. Weist (1965, p. 24) stated, "Water that is high in sodium in relation to calcium and magnesium will cause alkalinization of the soils that contain silt, fine clay, or organic fractions and result in poor tilth. In general, the sodium concentration must comprise more than half of the soluble cations before exchange is significant."

Evaporite deposits may occur in the basin fill. Although the presence of gypsum, halite, anhydrite, or other evaporite deposits were not observed in the drill cuttings, the chemical quality of water from wells DW-53 and USGS 3 in the northwestern part and center of the area indicated anomalously large concentrations of sodium, chloride, sulfate, and dissolved solids common to evaporite deposits. This ground-water chemistry is similar to the chemistry in aquifers that have interlayered evaporite deposits (Hem, 1970).

Chemical quality of ground water for irrigation use

The suitability of most water for irrigation depends on the amount and types of dissolved constituents in the water, on the soil type, and on the types of crops to be grown. A carefully planned balance of soil- and water-management practices in addition to proper use of soil additives could insure crop growth and prevent damage to the soil. Suitability of ground water for irrigation in the study area was evaluated on the basis of the salinity hazard, the sodium (alkali) hazard, the residual sodium carbonate (an indicator of the bicarbonate concentration), boron, and other dissolved constituents.

Salinity hazard

The salinity hazard depends on the concentration of dissolved solids and is normally estimated by field or laboratory measurements of specific conductance of the water, which is expressed in micromhos per centimeter at 25 °C. The specific conductance is an approximate measure of the total concentration of the ionized constituents in the water. On the basis of chemical analyses of water shown in table 2, dissolved solids in ground water in the study area can be estimated by multiplying the specific conductance by an average conversion value of 0.63.

U.S. Salinity Laboratory Staff (1954, p. 79-81) divided the salinity hazard of irrigation water into four classes with respect to conductivity (fig. 14):

Low-salinity water (C1) can be used for irrigation with most

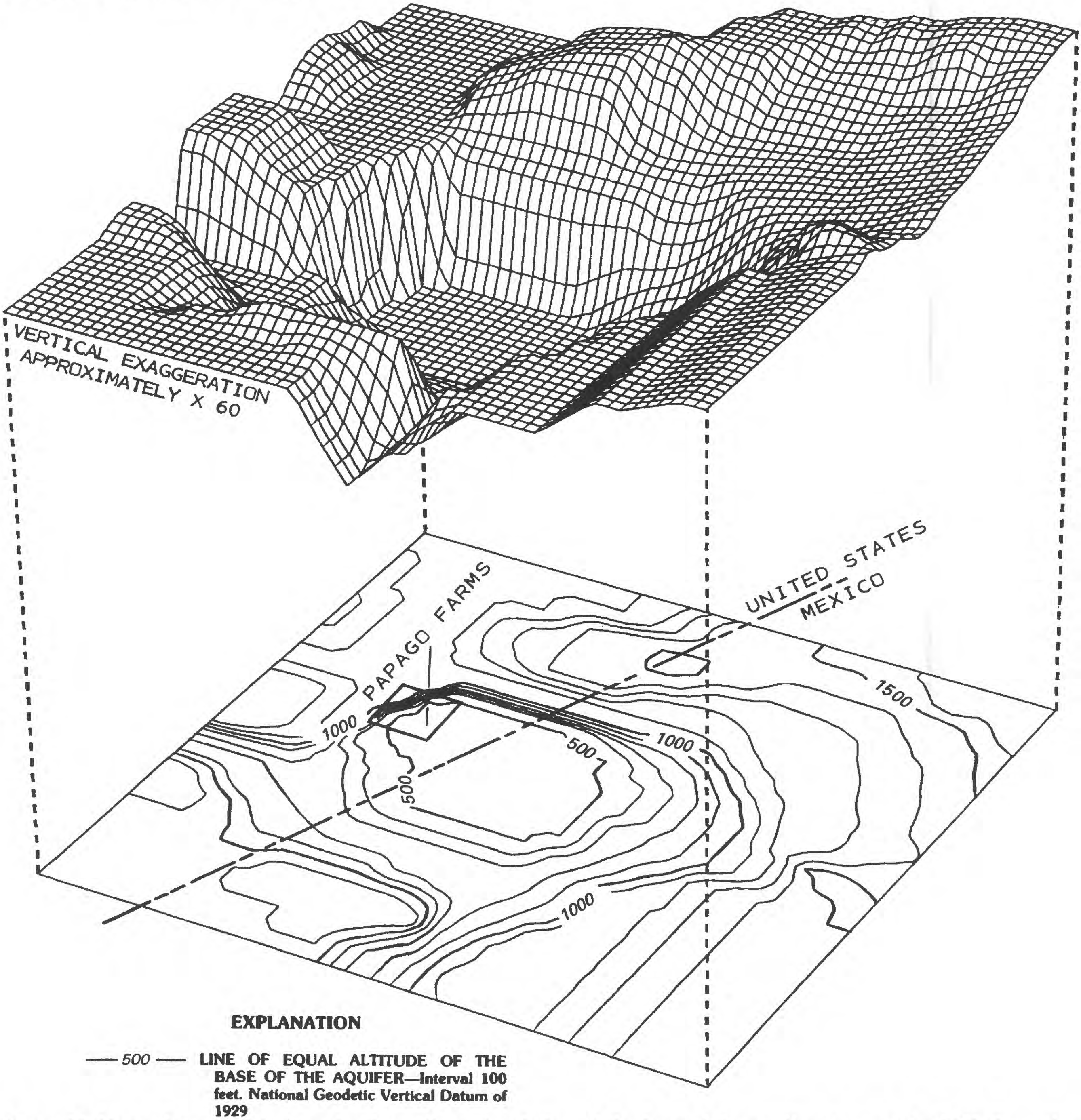


Figure 11. Lines of equal altitude and a three-dimensional view of the base of the aquifer at an angle of 30° above the horizontal from the southwest corner of the study area. The abrupt slope change in the center represents the vertical offset along the Mesquite Mountains and Molenitus faults.

crops on most soils with little likelihood that soil salinity will develop. Some leaching is required, but this occurs under normal irrigation practices except in soils of extremely low permeability.

Medium-salinity water (C2) can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.

High-salinity water (C3) cannot be used on soils with restricted drainage. Even with adequate drainage, special management for salinity control may be required and plants with good salt tolerance should be selected.

Very high salinity water (C4) is not suitable for irrigation under ordinary conditions, but may be used occasionally under very special circumstances. The soils must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching, and very salt-tolerant crops should be selected.

Thus, water of low conductivity generally is more suitable for irrigation than water of high conductivity. Irrigation water in the study area is classed as medium-salinity water (C2). Water in a few wells in the basin-center lakebed-clay deposits is

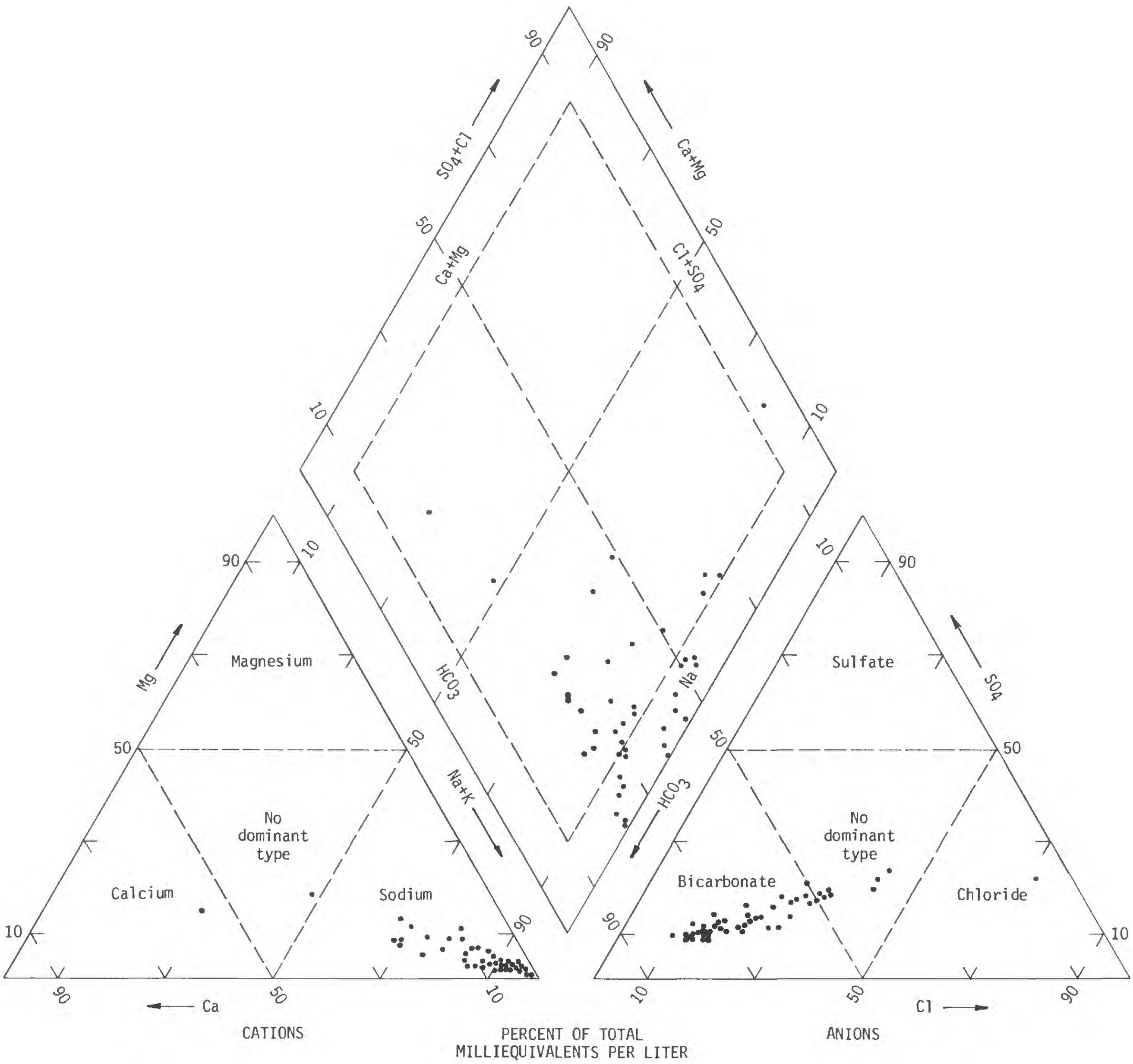


Figure 12. Percentages of chemical constituents in the well water and the classification of major water types.

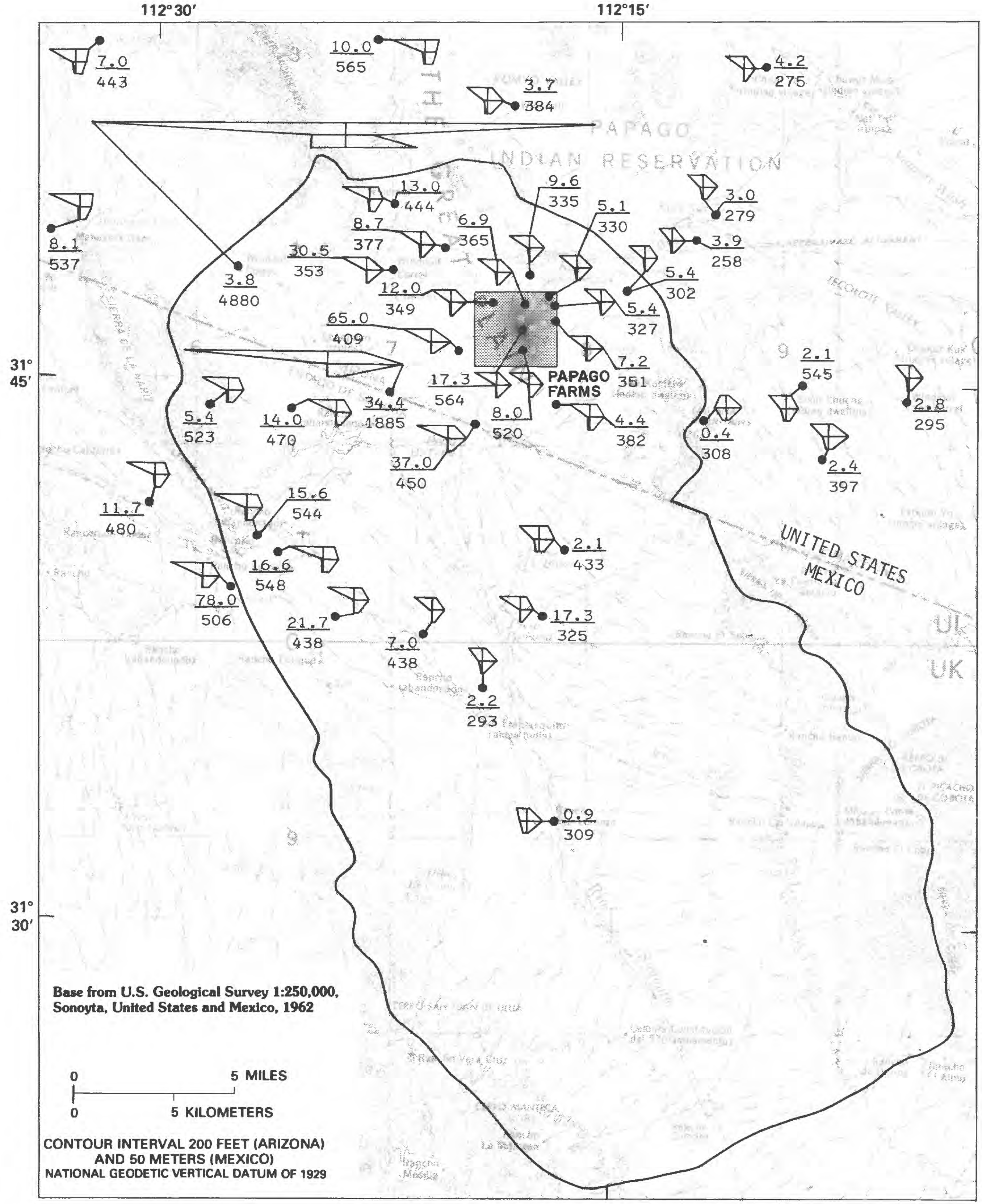


Figure 13. Ratio of sodium to calcium plus magnesium, dissolved solids, and distribution of chemical constituents in the well water.

classed as very high salinity water (C4). The specific conductance of water from selected wells is shown in table 2.

Sodium (alkalinity) hazard

The sodium or alkali hazard is indicated by the sodium-adsorption ratio (SAR), which is defined by the equation

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}, \qquad (2)$$

in which concentrations are expressed in milliequivalents per liter. The classification of irrigation water with respect to SAR is based primarily on the effect of exchangeable sodium on the physical conditions of the soil. The U.S. Salinity Laboratory Staff (1954, p. 81) classified irrigation water with respect to sodium hazard as follows:

Low-sodium water (S1) can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium. However, sodium-sensitive crops such as stone-fruit trees and avocados may accumulate injurious concentrations of sodium.

Medium-sodium water (S2) will present an appreciable sodium hazard in fine-textured soils having high cation-exchange capacity, especially under low-leaching conditions, unless gypsum is present in the soil. This water may be used on coarse-textured or organic soils with good permeability.

High-sodium water (S3) may produce harmful levels of exchangeable sodium in most soils and will require special soil management—good drainage, high leaching, and organic matter additions. Gypsiferous soils may not develop harmful levels of exchangeable sodium from such waters. Chemical amendments may be required for replacement of exchangeable sodium, except that amendments may not be feasible with waters of very high salinity.

Very high-sodium water (S4) is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity, where the solution of calcium from the soil or use of gypsum or other amendments may make the use of these waters feasible.

If the proportion of sodium among the cations is high, the alkali hazard is high; but if calcium and magnesium ions predominate, the alkali hazard is low. For ground water used for irrigation in the study area, the SAR ranges from medium salinity–low sodium hazard to high salinity–high sodium hazard. In ground water closely associated with the basin-center lakebed-clay deposits, the SAR generally is very high salinity–very high sodium hazard (table 2 and fig. 14).

Bicarbonate-ion concentration

The sodium hazard has a tendency to increase when irrigation water contains a high concentration of bicarbonate ions. In such water, calcium and magnesium tend to precipitate as carbonates, which increases the relative proportion of sodium in the water (U.S. Salinity Laboratory Staff, 1954). The concept of "residual sodium carbonate" (RSC) (Eaton, 1950) is a means of evaluating the bicarbonate-ion concentrations in water with exchangeable sodium in solution. The RSC of a particular sample of water is defined by the equation

$$RSC = (CO_3^{=} + HCO_3^{-}) - (Ca^{++} + Mg^{++}) \qquad (3)$$

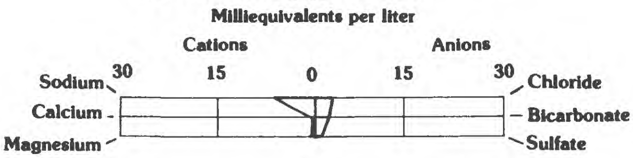
in which concentrations are expressed in milliequivalents per liter. The U.S. Salinity Laboratory Staff (1954, p. 81-82) concluded that irrigation water with an RSC of more than 2.5 mg/L is not suitable for irrigation purposes; whereas water containing 1.25 to 2.5 mg/L is marginal, and water containing less than 1.25 mg/L is probably suitable. The U.S. Salinity Laboratory Staff (1954) indicated, however, that these findings are tentative and that proper use of amendments to the water or soil might make it possible to use some marginal water for irrigation successfully.

The RSC for well water in the study area ranges from 0.0 to 18.7 (table 2); however, RSC for irrigation water ranges from 1.2 to 3.5. Thus, because of the bicarbonate-ion concentration, most well water in the study area is marginal to unsuitable for irrigation unless the soil or water is treated.

EXPLANATION

● 0.9 / 309 — **SELECTED WELL FROM WHICH A WATER SAMPLE WAS COLLECTED IN 1978-80—Upper number, 0.9, is ratio in milliequivalents of sodium to calcium plus magnesium. Lower number, 309, is dissolved solids in milligrams per liter. See table 2**

CHEMICAL-QUALITY DIAGRAM—Shows major chemical constituents in milliequivalents per liter. The diagrams are in a variety of shapes and sizes, which provides a means of comparing, correlating, and characterizing types of water



——— **BOUNDARY OF STUDY AREA**

Figure 13. Continued.

Boron

Boron in small amounts is essential to plant growth but is toxic at concentrations slightly higher than the optimum. The optimum level for irrigation water is 1 mg/L (National Academy of Sciences and National Academy of Engineering, 1974). As indicated in table 2, boron concentrations in the ground water rarely exceeded 1 mg/L except in a few isolated wells. One well, USGS 3, discharges water with 16.0 mg/L dissolved boron (table 2).

Chemical quality of ground water for public supply

Chemical-quality criteria used in determining the suitability of water for use in public-supply systems are generally more stringent than criteria for water to be used in

Table 2. Chemical analyses of water from pumping wells in and near

Well number or name (See fig. 1)	Date of sample	Temperature (°C)	Silica (SiO_2)	Boron (B)	Iron (Fe)	Manganese (Mn)	Arsenic (As)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)
Papago Farms-											
DW-2......	3-78	46	37	0.52	0.09	0.010	-----	8.1	1.5	110	3.2
DW-29.....	7-79	29	25	.27	0	.010	0.010	29	5.2	100	.8
DW-30.....	10-78	--	77	.37	.13	.010	-----	3.6	.3	140	1.5
DW-31.....	8-78	30	32	.45	.17	.004	-----	6.8	2.3	150	3.4
DW-32.....	6-54	--	30	----	----	-----	-----	13	2.8	184	----
DW-37.....	7-79	29	41	.16	.07	0	.015	16	5.0	79	3.2
DW-38.....	5-78	23	37	.46	.82	-----	.030	10	4.8	144	----
DW-46.....	10-57	30	38	----	.13	-----	-----	17	6.4	111	----
DW-53.....	9-78	28	35	1.40	.10	.020	-----	160	100	1,400	11
DW-58.....	5-78	27	48	.48	.15	-----	.034	11	4.4	167	----
DW-66.....	5-78	29	29	.28	.10	0	.015	3.0	0	97	1.4
La Lesna..	9-57	--	41	----	.02	-----	-----	57	8.8	33	----
PF-1......	3-78	44	53	.32	.12	0	-----	8.1	1.2	110	3.2
PF-2......	3-78	38	50	.27	.10	0	-----	6.8	1.1	110	2.5
PF-3......	9-78	26	52	.24	.12	.005	-----	13	2.3	94	3.3
PF-4......	7-80	27	43	.27	.01	.002	.036	4.4	1	120	1.9
PF-5......	3-78	27	38	.22	.10	0	-----	8.8	1.9	110	2.6
PF-6......	4-79	27	57	.24	.13	.010	.029	11	3.8	99	3.4
PF-7......	10-78	39	61	.31	.08	0	-----	7.5	1.8	120	4.5
PF-8......	7-79	51	60	.75	.04	.010	.020	12	1.6	110	3.1
PF-9......	10-80	39	37	.33	.03	.720	-----	14	2.6	150	4.2
PF-15.....	7-79	30	53	.23	.03	.010	.014	13	1.5	96	3.6
PFD-A.....	2-80	38	31	.30	.38	.004	.020	5	1.4	110	2.9
Toro 1....	11-57	30	35	----	----	-----	-----	18	2.6	77	----
Toro 3....	10-78	24	31	.20	.17	.005	-----	13	2.9	72	2.5
Range 7...	3-78	27	---	----	.04	-----	-----	1.6	.1	153	2.4
Range 10..	7-79	31	43	.17	.07	0	.020	29.0	5.8	93	4.2
USGS 1....	12-78	27	41	.21	.10	.007	.021	11.0	2.8	87	3.1
USGS 2....	10-78	25	27	.68	.19	0	.063	3.2	.4	270	.9
USGS 3....	11-78	25	18	16	.14	0	.960	.8	.2	790	2.9
USGS 4....	10-78	24	43	.50	.19	.008	.084	1.8	.3	150	.8
USGS 5....	12-78	29	42	.31	.11	.020	.021	8.2	2.5	120	4
USGS 6....	11-78	28	45	.22	.12	.009	.023	13.0	5.9	110	.6
Upper Rio											
10-01.....	5-81	31	61	0.35	0.02	<0.001	0.018	14.0	5.9	150	5.2
10-02.....	5-81	33	44	.30	<.01	.001	.070	5.1	2.1	160	3
12-01.....	5-81	28	29	.26	.02	.001	.013	29	11	110	2.2
22-07.....	5-81	30	47	.30	<.01	<.001	.050	7.9	2.5	160	3.9
23-01.....	5-81	29	48	.35	<.01	.001	.040	6.2	2.8	180	3.6
23-07.....	5-81	31	56	.40	.01	.001	.200	2.1	.0	180	1.9
23-09.....	5-81	36	48	.48	.02	.001	.400	4.5	.9	150	1.2
23-12.....	5-81	31	24	.20	.01	.001	.050	9.6	1.2	96	2.3
23-16.....	5-81	31	48	.40	<.01	.001	.060	5.5	2	190	3.2
24-08.....	5-81	28	31	.08	.01	.001	.030	22.0	4.7	76	2.6
24-15.....	5-81	34	23	.19	<.01	<.001	.030	3.7	.7	120	1.5
36-01.....	5-81	30	39	.11	<.01	.001	.030	35	11	56	2.5
APH-230...	5-81	32	51	1.70	.02	.004	.600	3.8	1.1	350	3.1

agriculture. The U.S. Environmental Protection Agency (1977a, b) has established national regulations and guidelines for the quality of water provided by public-supply water systems in the United States. Primary drinking-water regulations govern levels of constituents in drinking water that have been shown to affect human health. Secondary drinking-water regulations apply to levels of constituents that affect esthetic quality. The regulations express limits as "maximum contaminant levels," where contaminant means any chemical, biological, or radiological substance or matter in water. On the basis of such limits, water from most wells in the study area contains concentrations of most constituents that are less than the maximum contaminant levels and is acceptable for public-supply purposes. Water from many

the Papago Farms-Great Plain and upper Rio Sonoyta study area

Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3) + Nitrite (NO_2) as N	Dissolved solids, calculated	Specific conductance (micromhos at 25°C)	Hardness as $CaCO_3$	pH (field units)	Sodium adsorption ratio (SAR)	Residual sodium carbonate (RSC)
Great Plain										
220	26	31	9.2	---	335	535	26	7.7	9	3.1
300	44	37	1.1	1.5	397	688	94	----	5	3.1
250	23	23	10.0	1.3	353	588	10	----	19	3.9
200	63	68	2.9	3.7	444	722	26	7.9	13	2.8
170	91	128	1.8	6.8	565	936	44	----	12	2.0
200	18	25	2.1	1.5	295	464	61	----	4	2.1
153	69	104	6.4	---	443	770	46	8.2	9	1.6
237	45	43	2.0	1.1	384	603	69	7.3	6	2.6
400	850	2,100	1.4	4.5	4,880	8,168	810	----	21	0
178	69	114	2.4	---	537	858	45	8.1	11	2.0
200	18	19	2.1	1.5	275	430	8	7.7	15	2.8
233	21	15	1.2	3.6	308	446	178	7.3	1	.3
220	30	31	11.0	---	356	539	25	8.0	10	3.1
220	30	30	9.3	---	349	543	22	7.7	10	3.2
210	22	26	4.3	1.5	327	485	42	----	6	2.6
232	28	21	8.0	1.8	350	564	15	7.9	14	3.5
210	24	33	8.4	---	331	520	30	7.9	9	2.8
240	20	23	7.6	1.6	351	553	43	7.9	7	3.1
220	30	30	9.4	1.2	373	560	26	----	10	3.1
210	29	30	8.8	1.3	365	548	37	----	8	2.7
280	44	58	.7	0	450	746	46	7.8	10	3.7
220	22	23	4.3	1.2	330	498	39	----	7	2.9
219	23	28	7.7	2.6	329	528	18	----	11	3.3
200	17	25	1.4	1.0	279	432	56	7.2	6	2.2
180	18	22	1.6	1.4	258	425	44	----	5	2.2
246	---	-----	----	---	-----	844	4	10.7	32	3.9
180	37	44	2.9	1.6	355	545	96	----	4	1.1
190	23	36	2.3	1.8	302	473	39	----	6	2.4
170	45	59	12	2.2	450	770	10	----	24	4.2
1,140	160	280	54	.5	1,885	3,195	3	----	205	18.7
300	24	31	7.9	1.7	409	670	6	----	27	4.8
200	33	40	8.3	1.3	377	544	31	----	9	2.7
200	37	59	4.0	2.0	382	607	57	----	6	2.2
Sonoyta										
232	61	86	2.9	5.0	523	765	59	7.8	9	2.6
232	55	70	6.1	2.4	470	750	21	8.1	15	3.3
219	53	76	2.7	2.6	433	690	120	7.7	4	1.3
219	62	85	3.6	---	480	805	29	8.1	13	3.0
232	71	95	4.3	4.1	544	850	27	8.0	15	3.3
244	56	71	6.8	2.5	506	775	5	8.5	34	3.9
219	53	57	6.9	1.8	438	670	15	8.3	17	3.3
183	23	33	4.5	1.9	292	475	29	7.8	8	2.4
232	67	97	5.8	3.3	548	875	22	8.1	18	3.3
207	17	26	1.4	2.3	293	462	74	7.5	4	1.9
183	26	49	2.8	1.7	325	525	12	8.4	15	2.7
232	19	26	.9	1.2	309	480	130	7.4	2	1.2
439	94	140	2.5	.1	865	1,500	14	----	41	6.9

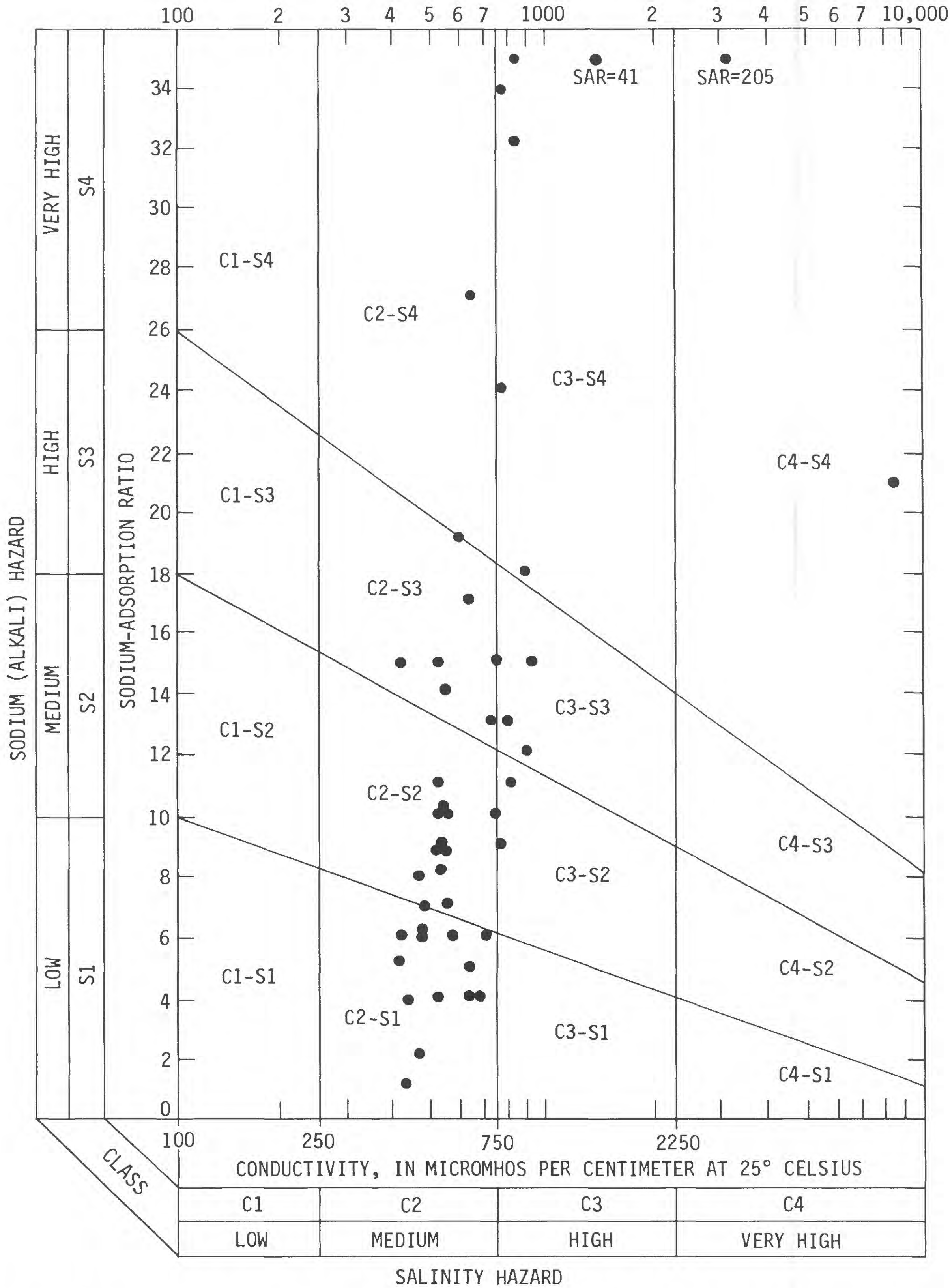


Figure 14. Classification of well water for use in irrigation based on electrical conductivity and sodium-adsorption ratio.

wells, however, contains concentrations of arsenic and fluoride that exceed the maximum contaminant level and thus is unacceptable.

Arsenic

The maximum contaminant level (primary limit) for arsenic accepted in water used for public-supply purposes is 0.050 mg/L. Ingestion of water containing arsenic exceeding this concentration presents a potential health hazard (U.S. Environmental Protection Agency, 1977a, b; Gough and others, 1979). Arsenic concentrations in well waters within the study area ranged from 0.010 to 0.960 mg/L (table 2; fig. 15). The arsenic appears to be more concentrated in the basin-center lakebed-clay deposits and may contaminate ground water that flows through and past the clays for a significant distance downgradient.

Fluoride

On the basis of the annual average of maximum daily air temperatures, the maximum acceptable fluoride concentration for public-supply water in the study area is 1.4 mg/L (U.S. Environmental Protection Agency, 1977a, b; Gough and others, 1979). Where the fluoride concentration is about 1.0 mg/L, no ill effects will result and tooth decay generally is less than where drinking water contains little or no fluoride. Excessive fluoride in the drinking water results in discoloring of teeth, especially in children. Fluoride exceeds 1.4 mg/L in most of the ground water in the study area (table 2; fig. 15). Fluoride concentrations range from 0.7 to 12.0 mg/L and average 4.9 mg/L. A value of 54 mg/L was determined for well water at USGS 3, but this value is not indicative of basin-wide fluoride values and thus was not averaged with other values.

Dissolved solids

The maximum contaminant level (secondary limit) for dissolved solids in public-supply water is 500 mg/L (U.S. Environmental Protection Agency, 1977a). Dissolved-solids concentrations in the study area range from 258 to 4,880 mg/L and average 530 mg/L (table 2; fig. 13). More than 80 percent of the sampled wells contain concentrations that are less than 500 mg/L.

Ground-Water Budget

A ground-water budget is an accounting of the inflow to and outflow from the aquifer and changes in ground water in storage. If inflow equals outflow and if the change in the volume of water in storage is zero, the aquifer is in an equilibrium or steady-state condition. Equilibrium is reflected by the absence of long-term trends of changing water levels. If total inflow does not equal outflow, the aquifer is in a nonequilibrium or transient condition, and the change in the volume of water in storage is reflected in the changing water levels.

Inflow

The primary inflow to the aquifer is recharge from the infiltration of precipitation and runoff along the mountain fronts and underflow of ground water into the area beneath the San Simon and Chukut Kuk Washes. Because of high evaporation, transpiration, and low precipitation, little or no recharge occurs through the interstream parts of the basin floor. Infiltration through the permeable stream-channel deposits may allow some direct recharge to the aquifer through the streambeds; however, the amount is small and probably has no significant effect on the total inflow.

Recharge

Some precipitation that falls in the mountains infiltrates the aquifer as recharge. Most of this infiltration is thought to occur through the heads of alluvial-fan and colluvial deposits that cover the pediments along the mountain fronts, although few data exist to support this contention. Some water may enter the aquifer through the bedrock of the mountains at the contact with the basin fill. Recharge that enters as infiltrating runoff along the mountain fronts in relation to the amount that passes through the bedrock is not known. The total estimate of recharge reflects all water that enters the aquifer along the margins of the basin. An estimated 5 to 10 percent of the annual rainfall in the mountains recharges the aquifer (Water Resources Research Center, 1980). The average annual recharge from 64,000 acres of mountains is estimated to range from 1,800 to 7,500 acre-ft/yr. Most of the mountain recharge originates in the upper Rio Sonoyta area, and a large part is contributed by Sierra del Cobre. The recharge rate of 1,800 to 7,500 acre-ft/yr represents 30 to 125 acre-ft/yr of recharge per mile of mountain front surrounding the basin.

Underflow into the study area

Ground water that enters through the basin fill beneath the Chukut Kuk and San Simon Washes constitutes the underflow and is estimated by the equation

$$Q = KIA \tag{4}$$

where

Q = discharge, in cubic feet per day;
K = hydraulic conductivity, in feet per day;
I = hydraulic gradient (dimensionless); and
A = cross-section area of flow, in square feet.

Values for variables in the equation were determined from cross-sectional areas produced by detailed gravity modeling (Greenes, 1980) and from hydraulic gradients derived

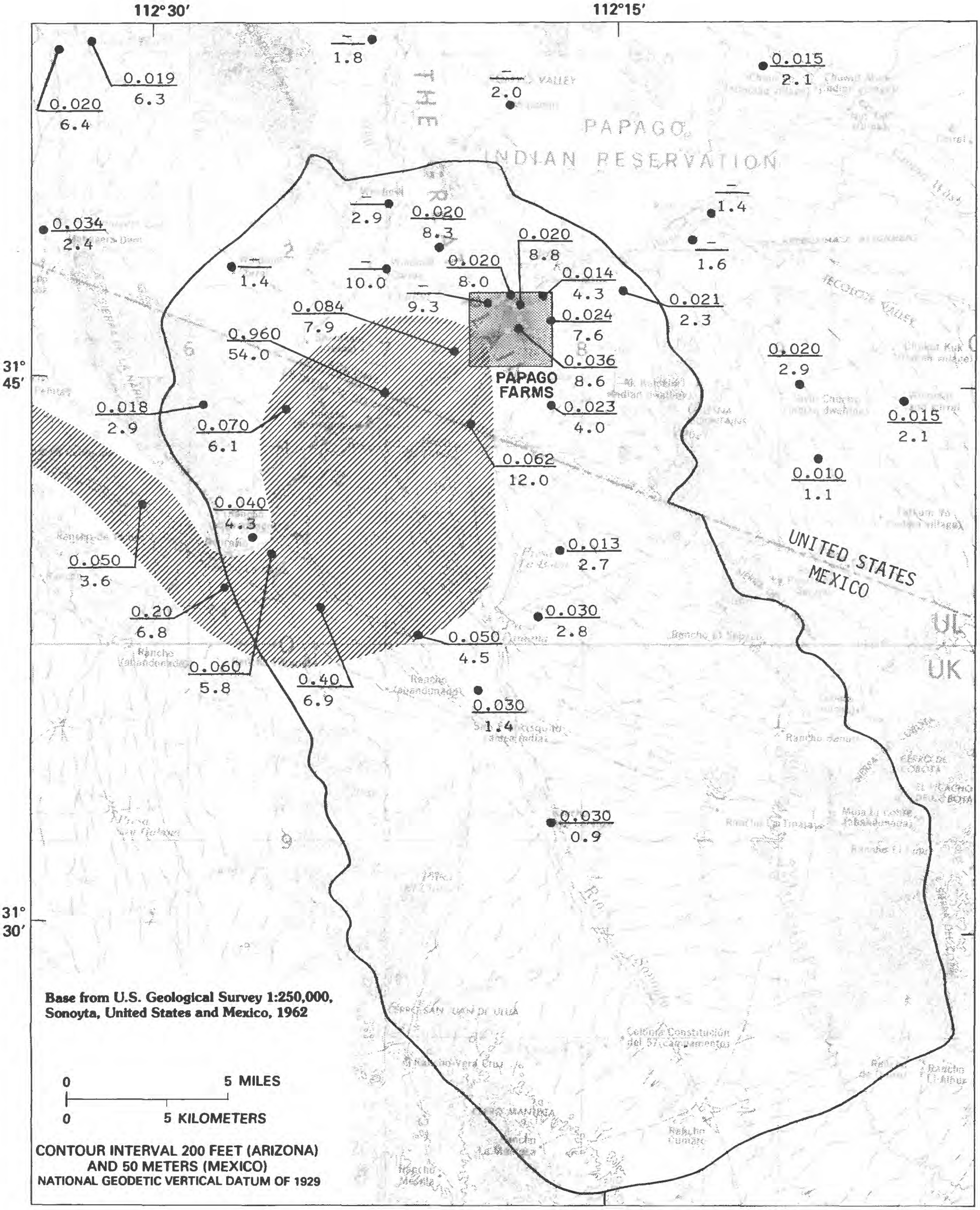


Figure 15. Distribution of arsenic and fluoride in well water.

from the steady-state water levels (fig. 9); a value of 10 to 50 ft/d was used for hydraulic conductivity.

For the San Simon Wash entry point, the estimate of steady-state underflow ranged from 50 to 150 acre-ft/yr. Underflow in the Chukut Kuk entry point between Kots Kug and Papago Farms was estimated to range from 2,000 to 4,000 acre-ft/yr.

Outflow

Outflow from the aquifer occurs as underflow in the basin fill beneath the Rio Sonoyta just south of Cerro La Nariz and as ground-water withdrawals by pumping wells. Because depth to water in the study area is deeper than plant-transpiration and surface-evaporation effects, losses owing to evaporation and transpiration were negligible and not considered significant outflow.

Underflow out of the study area

Underflow of ground water through the basin fill at the outflow point was estimated to be the quantity of water equal to the steady-state inflow. Total inflow estimated for all sources ranges from 3,800 to 11,500 acre-ft/yr. Total underflow out of the study area, therefore, is in this range of values.

To test the feasibility that underflow fell within the range of values estimated for total inflow, equation 4 was used to compute steady-state underflow out of the system. Underflow was estimated to be between 1,500 and 4,500 acre-ft/yr using a hydraulic gradient from figure 9, a cross-sectional area based on saturated thickness of 700-900 ft, a valley width of 2 to 3 mi, and hydraulic conductivities of 70 to 100 ft/d for stream-channel deposits. Wide ranges in estimates for total inflow and outflow are due to errors inherent in the methods used to estimate the flow.

EXPLANATION

AREA IN WHICH ARSENIC CONCENTRATION IS EQUAL TO OR MORE THAN 0.050 MILLIGRAMS PER LITER FOR PUBLIC SUPPLY

0.030 / 0.9 — SELECTED WELL FROM WHICH A WATER SAMPLE WAS COLLECTED—Upper number 0.030, is arsenic concentration in milligrams per liter. Lower number, 0.9, is fluoride concentration in milligrams per liter

BOUNDARY OF STUDY AREA

Figure 15. Continued.

Ground-water withdrawals

Significant withdrawal of ground water from the Papago Farms area occurred between 1957-60, when the farms were first developed and then abandoned. From 1960 to 1978, development of the aquifer at Papago Farms was slight and consisted of a few widely scattered livestock wells that were estimated to have withdrawn less than 10 acre-ft/yr. The 18-year dormant period between farming operations allowed the hydrologic system north of the international boundary to return to steady-state conditions (L. A. Heindl, hydrologist, U.S. Geological Survey, written commun., 1976).

Between 1978 and the end of 1981, about 11,300 acre-ft of water was withdrawn for irrigation at Papago Farms. From June 1978 to November 1980, irrigation of crops at Papago Farms was seasonal and water use was at a peak in the summer months. After November 1980, alfalfa was planted, and irrigation water was used year round. Withdrawal rates increased from 3,800 to 5,300 acre-ft/yr.

Information was not available to indicate when ground-water withdrawals for irrigation began in the upper Rio Sonoyta area. High-altitude infrared imagery indicates that some land was irrigated as early as 1973 and that substantial areas were irrigated by 1976. Aerial photography indicates that about 2,700 acres and about 4,000 acres were irrigated in 1977 and 1980, respectively (U.S. Section, International Boundary and Water Commission, written commun., 1981). The estimated pumpage to irrigate these lands was about 12,000 acre-ft in 1977 and about 18,400 acre-ft in 1980.

Ground-water withdrawals in the upper Rio Sonoyta area do not appear to have an effect on water levels in the Papago Farms-Great Plain area. The virtually impermeable basin-center lakebed-clay deposits act as a ground-water barrier between Papago Farms and irrigated areas to the south.

Changes in Ground-Water Storage

Recoverable ground water in storage is the volume of water that is available to move from the pore spaces in the aquifer to wells. Storage is directly proportional to the saturated thickness and varies with changes in the water table. If withdrawals exceed inflow, water levels will decline and the amount of ground water in storage will decrease. In the study area, a minimum estimate of the amount of recoverable water in storage in the upper 400 ft of the aquifer may be obtained by multiplying the specific yield by the volume of saturated material. Using the estimated basin-wide average specific yield of 10 percent for the upper 400 ft of the aquifer in 1978-80, water in storage was about 10 million acre-ft. A combined withdrawal rate of 23,700 acre-ft/yr for the Papago Farms-Great Plain area and the upper Rio Sonoyta area in 1981 is reduced by an annual estimated recharge of 3,200 acre-ft/yr; therefore, about 20,500 acre-ft/yr of water was removed from storage in 1981.

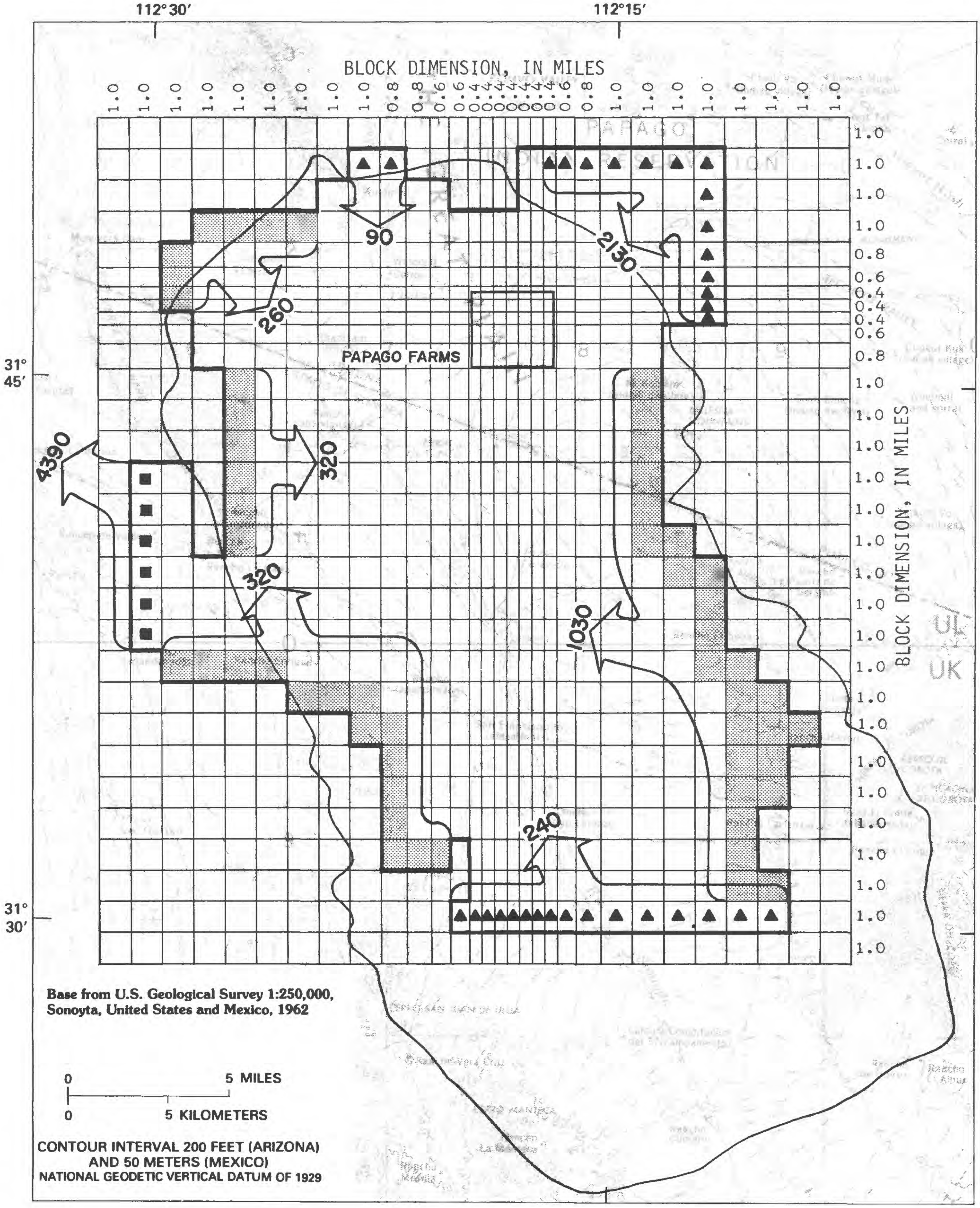


Figure 16. Finite-difference grid and boundary conditions used in the numerical ground-water flow model.

Simulation of Ground-Water Flow

A ground-water flow model was developed to mathematically synthesize the hydraulic characteristics and water-budget components as a means of evaluating how well all hydrologic information fit together as a reasonable representation of the actual ground-water system. A numerical ground-water flow model is a group of mathematical equations that approximate the ground-water flow through an aquifer as a function of the hydraulic characteristics of the aquifer and rates of inflow and outflow.

Detailed discussions of ground-water model theory and the basis of model development have been given by Pinder and Bredehoeft (1968) and Trescott and others (1976). The method involves solving finite-difference approximations of the partial differential equations of two-dimensional ground-water flow and represents the aquifer as a two-dimensional grid or network of blocks. Average aquifer conditions for a block are assigned at a point or node in the center of each block. The grid of the model was designed on a true north-south map orientation (fig. 16). Block sizes change uniformly from 1 mi on a side outside Papago Farms to 0.4 mi on a side at Papago Farms. The purpose of reducing the block size at Papago Farms was to (1) reduce the effect of the boundary conditions on drawdown at Papago Farms, (2) reduce the Papago Farms simulation area to a size that would place one irrigation well in each block, and (3) simulate rapid change in transmissivities caused by abrupt changes in saturated thickness near Papago Farms.

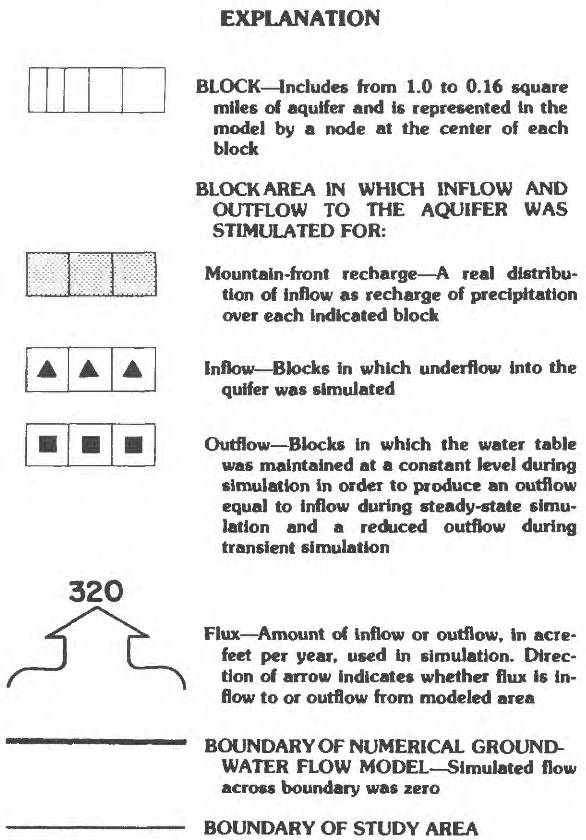


Figure 16. Continued.

Any model is at best an approximation of the real hydrologic system because not all the characteristics of the actual system can be included. Simplifying assumptions are required to make the problem manageable. The analysis is based on the following general assumptions:

1. All flow in the aquifer is unconfined, two-dimensional, and has no vertical component of flow.
2. Flow across boundaries is perpendicular to the boundary.
3. The aquifer is homogeneous within a given block of the finite-difference grid.
4. The bottom of the deepest part of the aquifer is arbitrarily cut off at 500 ft above NGVD of 1929, which is 200 ft below the deepest finished well in the study area.
5. Water levels along the margins of the basins are maintained by recharge from the immediately adjacent mountains and hills.
6. Estimates of quantity and distribution of available inflow are reasonable.
7. The averaged pumping rates used during the pumping periods of calibration adequately represent the stress on the aquifer.
8. The water-level contours extend up to and beyond the boundaries, especially in inflow and outflow sections of the study area.
9. Water-level contours shown in figure 9 represent steady-state conditions in the Papago Farms-Great Plain area in 1978 and the upper Rio Sonoyta area in 1980.

Model Boundaries and Data Input

All model boundaries (fig. 16) coincide with the aquifer limits defined by geohydrologic interpretations. In many areas the aquifer boundaries coincide with the subsurface contact of the bedrock and basin-fill deposits. Recharge near these boundaries represents infiltrating runoff at the surface. Constant-flux boundaries coincide with underflow areas in the northern part of the study area. The six nodes at the outflow point near the south end of Sierra de la Nariz were maintained as constant-head blocks during simulation. As a result, the model calculated the outflow through the six nodes at any stage of simulation on the basis of hydrologic conditions upgradient from the outflow area.

Input to the model included data that describe the physical area and saturated thickness of the aquifer. In general, these data were not changed during simulation and calibration. Reasonable estimates of inflow, outflow, and hydraulic conductivities were input and modified within the ranges discussed in the section entitled "Ground-Water Budget" to achieve a steady-state calibration.

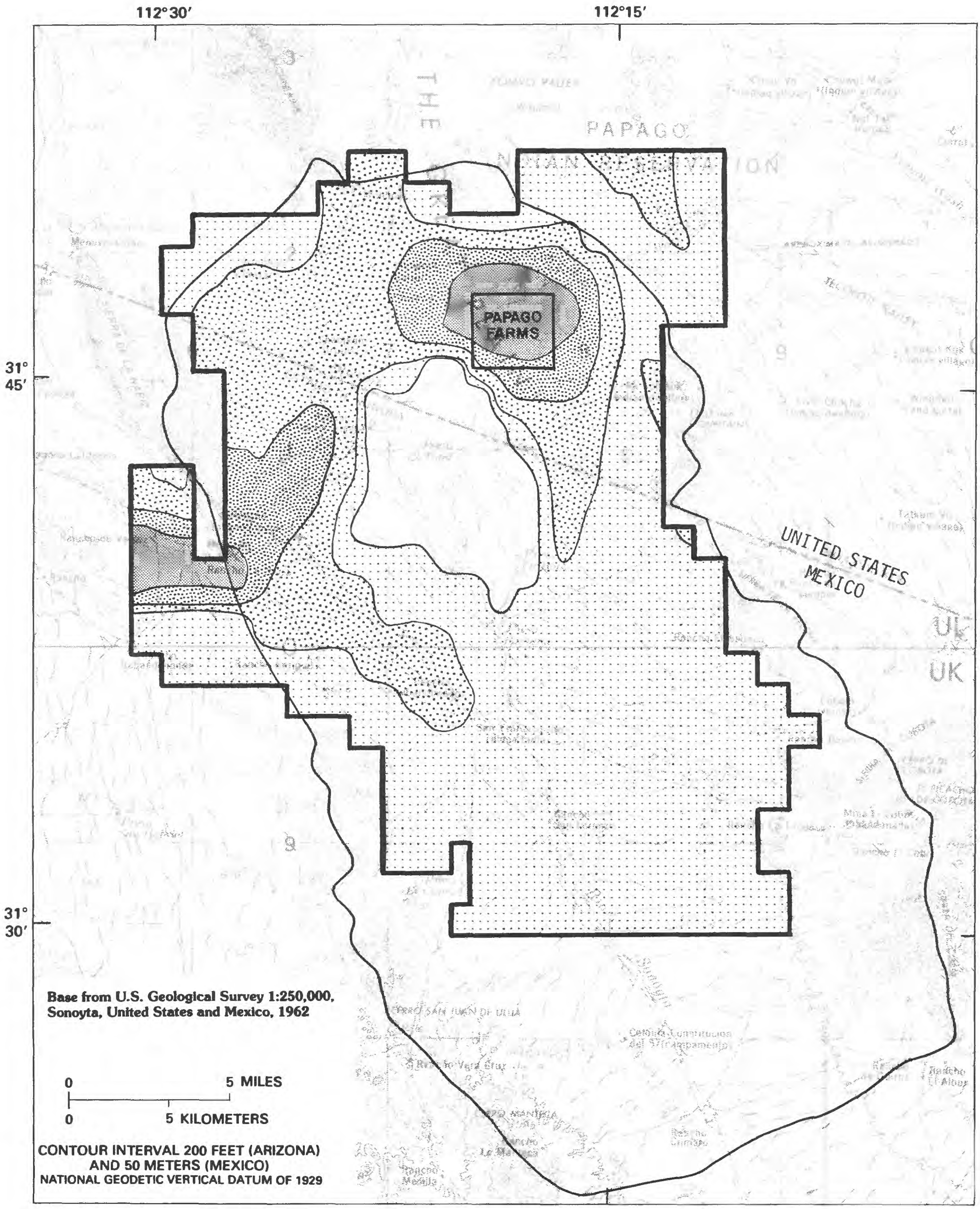


Figure 17. Distribution of hydraulic conductivity used in the steady-state simulation.

Calibration and Model Development

Calibration and development of the ground-water model used the estimated aquifer characteristics and water-budget components. By trial-and-error process, the estimated parameters were adjusted until a reasonable simulation at each node was obtained. The calibration was done for steady-state conditions and transient conditions.

Steady-state analysis

The steady-state analysis determined a reasonable distribution of hydraulic conductivity and boundary flux within the limits of the conceptualized geohydrologic conditions. Hydraulic conductivities were successively and systematically modified from the outflow point upgradient to the inflow areas until simulated and measured steady-state water levels matched. Steady-state saturated thickness and estimated values for recharge and underflow were fixed. This trial-and-error method of changing the hydraulic conductivities was governed to some extent by changes indicated by a preliminary flow-net analysis. Hydraulic conductivities that were already calibrated downgradient remained unaffected by later modifications upgradient. The resultant hydraulic conductivity of the aquifer used in the steady-state analysis is shown in figure 17.

After establishing a reasonable match of the simulated and measured water levels through modification of the hydraulic conductivities, recharge and underflow were redistributed and changed in order to refine the shape of the water-table contours near the boundaries. Blocks for which underflow or recharge was simulated for steady-state conditions are shown in figure 16 and tabulated in table 3.

A comparison of the measured and simulated water levels is shown in figure 18. The difference between the observed steady-state water levels and the simulated water levels at each node in the Papago Farms-Great Plain area ranged from 0 to 8 ft and averaged 4 ft. Water-level differences in the upper Rio Sonoyta area ranged from 0 to 50 ft and averaged about 20 ft. These average differences are within the accuracy of the data used to construct the steady-state water-table map for the particular areas (fig. 9).

Transient analysis

Transient analysis was done by adding specific yield, pumpage, and time to the steady-state model. The simulated water levels from the steady-state model were used as initial water levels in the transient model so that resulting changes would be caused entirely by simulated withdrawals.

Seven pumping periods were used in the transient-calibration phase. The first six pumping periods reflect the seasonal variation in pumping observed at Papago Farms (table 4). The seventh pumping period simulated not only withdrawal of ground water at Papago Farms but also withdrawal in the upper Rio Sonoyta area. Simulation of pumping in the upper Rio Sonoyta area was not initiated until the seventh pumping period because the water levels used to calibrate the steady-state model in this area generally reflect late 1980 water levels and, to some extent, prior ground-water withdrawals. Furthermore, calibration of a transient model in the Papago Farms-Great Plain area was exclusive of withdrawal effects in the upper Rio Sonoyta area. This calibration was made possible by the barrier effect of the basin-center lakebed-clay deposits. These impermeable clays essentially separate the two major pumping centers to the north and south of the basin-center lakebed-clay deposits. Ground-water withdrawal from wells situated in Mexico along the eastern margin of the Sierra de la Nariz and close to the international boundary could have an effect on transient

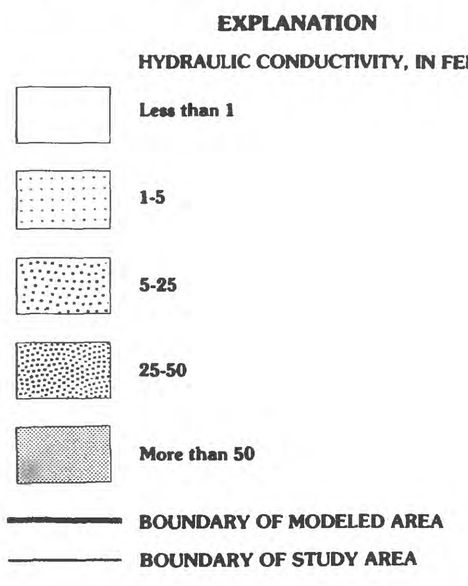


Figure 17. Continued.

Table 3. Steady-state simulated water budget of the aquifer in the Papago Farms-Great Plain and upper Rio Sonoyta study area

Inflow:		
Recharge from infiltration of rainfall		
Mesquite Mountains and near ground-water divide	260	
La Lesna Mountains, Sierra de la Alesna, and Sierra del Cobre	1,030	
Western mountains south of Rio Sonoyta	320	
Sierra de la Nariz	320	
Total		1,930
Underflow boundary		
Southern boundary of model	240	
Beneath Chukuk Kuk Wash	2,130	
Beneath San Simon Wash	90	
Total		2,460
Total inflow		4,390
Outflow:		
Constant head nodes at outflow point of flow system	4,390	
Total outflow		4,390

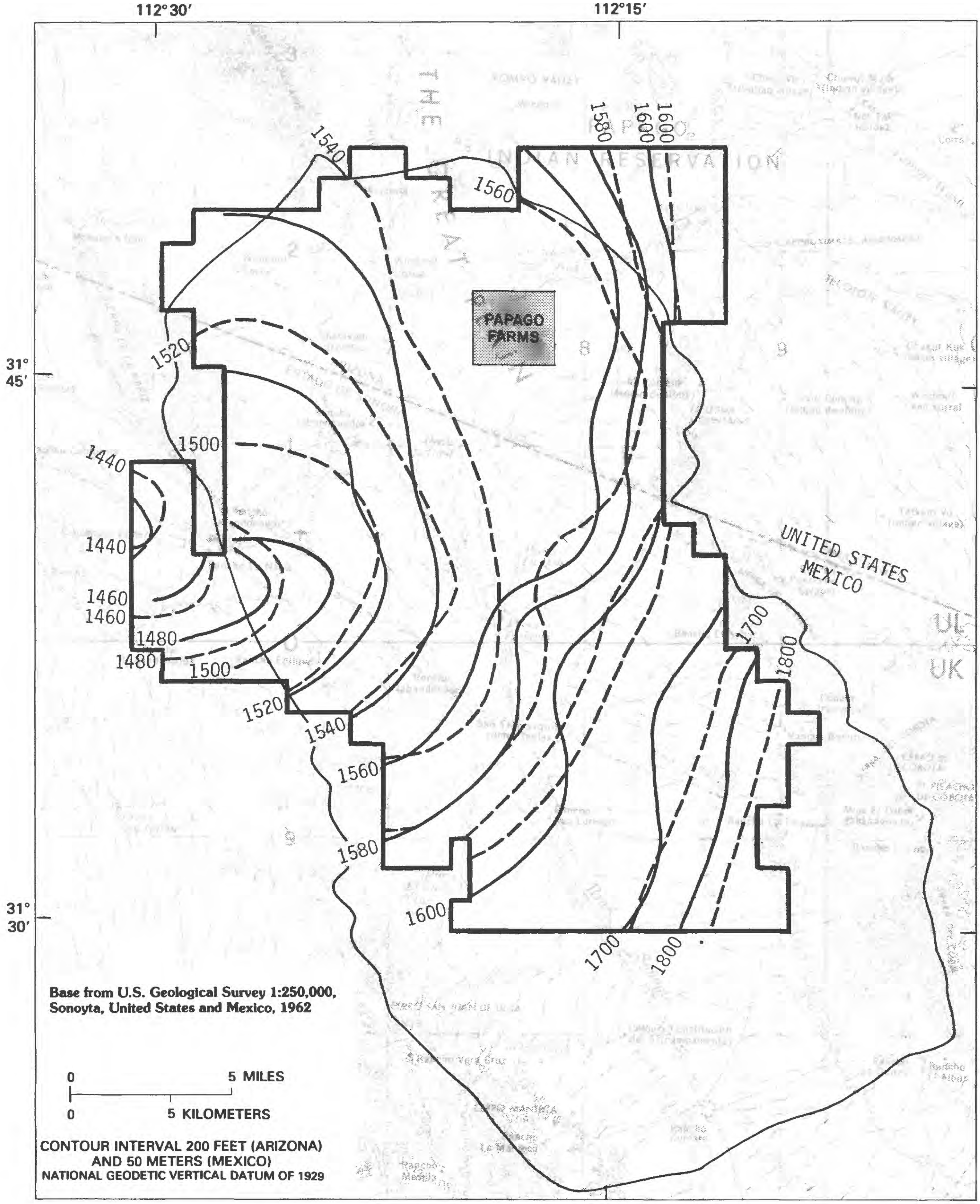


Figure 18. Distribution and comparison of measured and simulated water levels for the steady-state system.

calibration in the Papago Farms-Great Plain area. Withdrawal from these wells, however, was minimal during the time simulated in the first six pumping periods. Pumping along the west margin of the basin-center lakebed-clay deposits did increase in 1981 and is reflected in the pumpage values input to the seventh pumping period—1981-82.

For input to all seven pumping periods, the total observed withdrawal was converted to a rate of withdrawal for each period. In this manner the rate of ground-water withdrawal was averaged uniformly over each pumping period for each model block with a pumping well.

In order to calibrate the transient model in the Papago Farms-Great Plain area, changes in water levels in five observation wells located at varying distances around Papago Farms were monitored on a semiannual basis from 1978 to 1981. Simulated water-level declines were matched to those observed in the observation wells by altering specific-yield values in the model. Withdrawal from the scattered livestock wells in the area was considered to be negligible.

Water levels in four of the five wells were observed to have declined during the calibration period (fig. 19). Some of the wells showed more decline than others. The wells showing larger values of drawdown are generally closer to the pumping center and thus more affected by pumping.

The pumping rates used to simulate withdrawal in the study area were based on consumptive use of water for specific crops over a known amount of cultivated acreage. Since discharge from irrigation wells in the study area generally is not metered, calculating the consumptive use of water by certain plants is a reasonable method of estimating water demand for a particular crop (Blaney and Criddle, 1962; Erie and others, 1965). About 5,000 acres were being cultivated in the study area in 1980. Cultivated crops in the upper Rio Sonoyta area—cotton and wheat—were determined by spot checks in the field; crops at Papago Farms—alfalfa, sorghum, wheat, sudan, and barley—were determined from farm-management records. Consumptive use of water by crops for an environment and conditions that are similar to the study area is discussed by Blaney and Criddle (1962) and Erie and others (1965). Values for consumptive use were

EXPLANATION

— —1540— — **CALCULATED WATER-LEVEL CONTOUR—Altitude of the water level as calculated by the steady-state numerical flow model. Interval 20 and 100 feet. National Geodetical Vertical Datum of 1929**

——1540—— **WATER-LEVEL CONTOUR—Altitude of the water level prior to 1978 (from fig. 9). Interval 20 and 100 feet. National Geodetic Vertical Datum of 1929**

BOUNDARY OF MODELED AREA

BOUNDARY OF STUDY AREA

Figure 18. Continued.

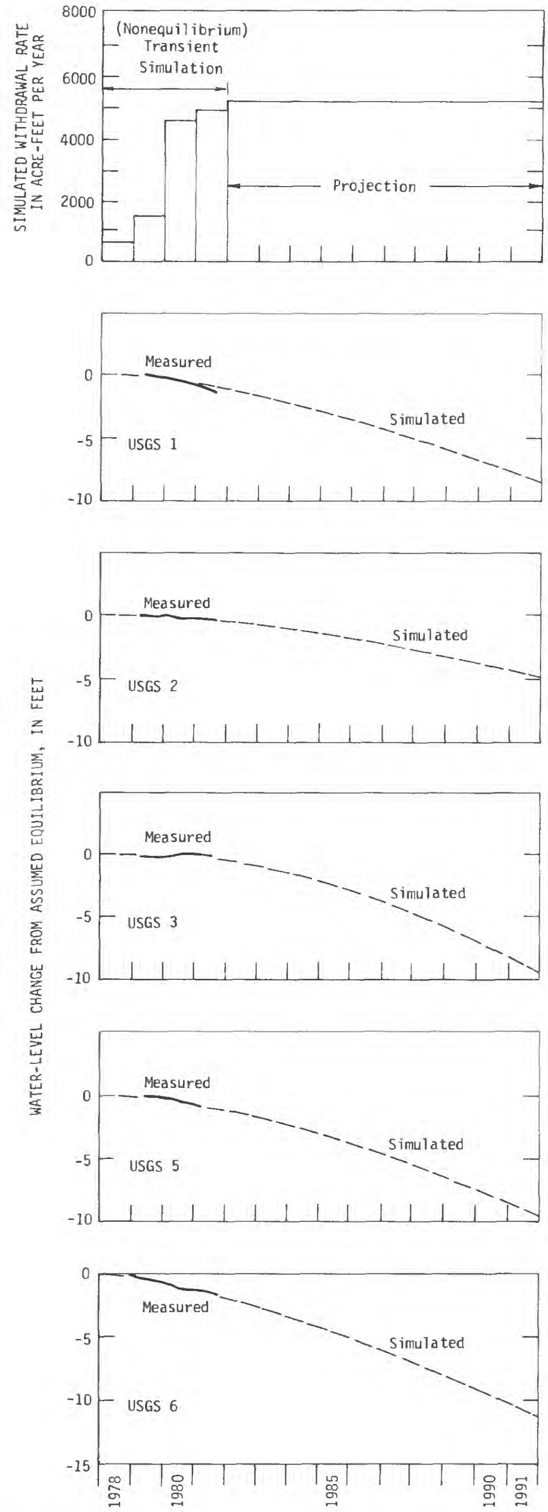


Figure 19. Estimated and projected ground-water withdrawals and water-level changes for five test wells near Papago Farms, 1978-91.

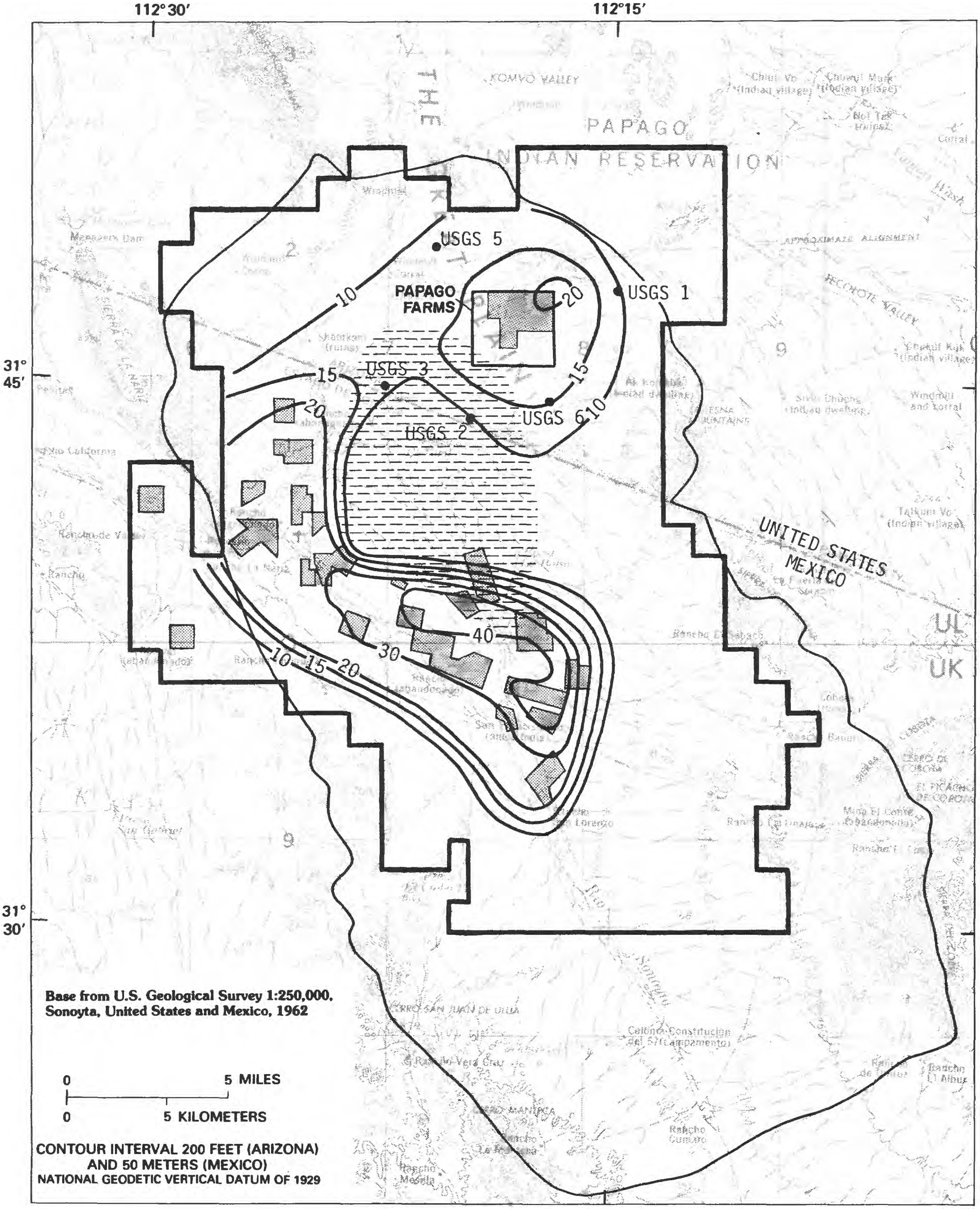


Figure 20. Distribution of irrigated acreage, 1980, and simulated water-level declines, 1991.

used to estimate pumpage for the irrigated acreage shown in figure 20. Thus, on the basis of acreage and crop type, about 23,700 acre-ft of ground water was pumped from the aquifer system in the study area in 1981. This value was used as the average annual rate of withdrawal for the $3^1/_2$ year transient-calibration period.

Transient calibration involved adjusting the specific-yield values until computed water levels matched the measured water levels in the five observation wells for the $3^1/_2$ year transient-calibration period. Changes in the specific yield have a direct effect on water available from storage and the amount of drawdown near a discharging well. A 50-percent change in the inflow to the aquifer did not have as much effect on drawdown as did a 1-percent change in specific yield. The final distribution of simulated specific yield used in the model is shown in figure 21. Using these specific yields, computed drawdowns in the five observation wells agreed within 1 ft with observed declines for the transient-calibration period (fig. 19).

Specific yields in the southern part of the upper Rio Sonoyta area were selected on the basis of the geohydrology and lithology (Johnson, 1967) and extrapolated on the basis of comparisons of specific-yield values determined by simulation for the Papago Farms-Great Plain area (fig. 21). The limited amount of available water-level change data in the upper Rio Sonoyta area, however, precluded testing the credibility of the distribution of specific yield; therefore, the model is not considered calibrated for this area.

Table 4. Pumping periods, total withdrawal, and withdrawal rates used in transient analysis of the ground-water system in the Papago Farms-Great Plain and upper Rio Sonoyta study area

Pumping period	Area	Approximate total withdrawal (in acre-ft)	Withdrawal rate (in ft^3/s)
June to October 1978--	Papago Farms	560	2.3
October 1978 to April 1979-------	do.	0	0
April to October 1979-----	do.	1,600	4.4
October 1979 to March 1980-------	do.	0	0
March to November 1980----	do.	3,800	7.8
November 1980 to January 1981-----	do.	0	0
January 1981 to January 1982-----	do.	5,300	7.2
Do----------------	Upper Rio Sonoyta	18,400	25.2

EXPLANATION

APPROXIMATE AREA OF IRRIGATED ACREAGE, 1980—Modified from International Boundary and Water Commission (written commun., 1981)

— 10 — LINE OF EQUAL SIMULATED WATER-LEVEL DECLINE—Interval 5 and 10 feet

● USGS 6 WELL FOR WHICH A MEASURED AND SIMULATED HYDROGRAPH WAS DRAWN—Well name, USGS 6, is that used on hydrograph shown in figure 19

APPROXIMATE AREA OF THE BASIN-CENTER LAKEBED-CLAY DEPOSITS

BOUNDARY OF MODELED AREA

BOUNDARY OF STUDY AREA

Figure 20. Continued.

Limitations and Use of the Model

The model reasonably simulates observed water levels in the ground-water system of the Papago Farms-Great Plain area and with somewhat less accuracy simulates water levels in part of the upper Rio Sonoyta area. The transient-simulation period, however, was 3½ years, and inaccuracies between simulated and measured water-level declines could increase rapidly over long projections. Projections of future drawdowns using the model, therefore, should be limited to less than 10 years. In order to make the model more versatile as a management tool, a transient-calibration period on the order of 5 to 10 years is needed. In addition to a longer calibration period, long-term water-level changes and rates of withdrawal of ground water are needed for wells in the study area, but mainly in the upper Rio Sonoyta area. Such data can be collected as part of normal farm-management routine.

The calibrated model can be used to estimate future short-term drawdowns in the Papago Farms-Great Plain area. Predictions of future drawdowns in the upper Rio Sonoyta area, however, are shrouded by a high degree of uncertainty because of the sparsity and reliability of data south of the basin-center lakebed-clay deposits. Predicted drawdowns produced by the model for the upper Rio Sonoyta should be used qualitatively as a rough estimate of order of magnitude in drawdown and to roughly delineate the areal spread of a regional cone of water-level decline.

Stresses imposed on the aquifer during transient simulation are withdrawal rates for 1978-82. Greater future stresses, however, may cause unanticipated responses by the aquifer, such as delayed drainage, intersection of drawdown cones, and interception of drawdown cones with no-flow boundaries. Such responses may affect the model validity and may require modifications.

Projected Effects of Ground-Water Withdrawal From 1982 Through 1991

Ground-water conditions from 1978 through 1981 in the Papago Farms-Great Plain area could be reasonably simulated using the transient model. The assumption was made,

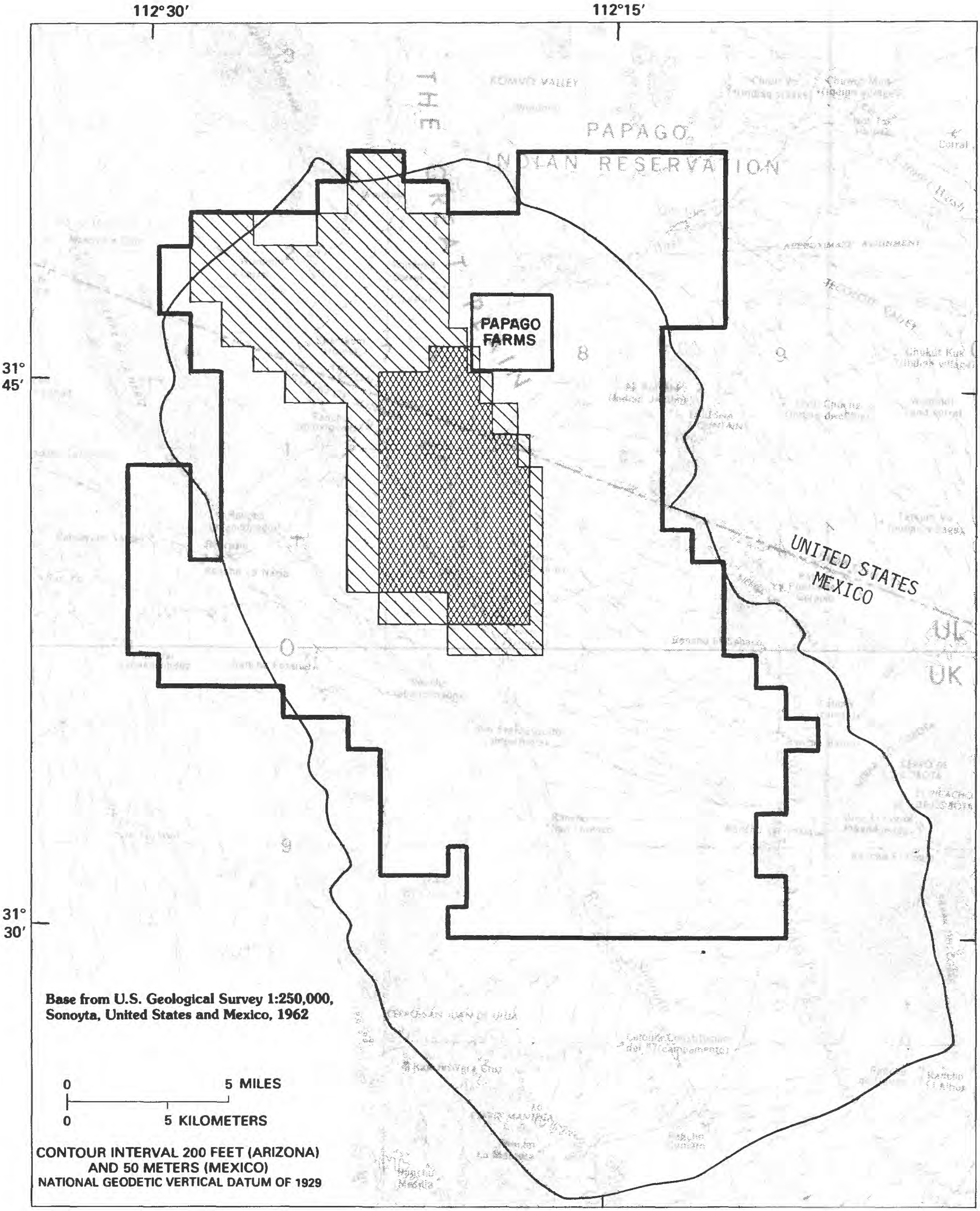


Figure 21. Distribution of specific yield used in the transient simulation.

therefore, that the model could be used to estimate the effects of projected ground-water withdrawal in 1991 in the Papago Farms-Great Plain area and, to a much lesser extent, the upper Rio Sonoyta area. The projections were most useful in delineating projected regional cones of water-level decline, shape and development of the regional cones of decline, and time of intersection of cones from various pumping centers. Simulated water-level changes discussed in this section, however, present average conditions distributed over an individual block of the model. Simulated water levels do not represent water levels in specific pumping wells.

Pumping rates used for simulation and calibration of the pumping period, 1981-82 (table 4), were used for the simulated projection period from 1982 through 1991. These rates assume no expansion of irrigated acreage and no change in agricultural practices in the study area. For the 10-year projection period, an estimated 237,000 acre-ft of ground water was withdrawn—53,000 acre-ft at Papago Farms and 184,000 acre-ft along the Rio Sonoyta and eastern margin of the Sierra de la Nariz.

The projected simulated conditions for 1991 indicate that cones of water-level decline at Papago Farms intersect cones of water-level decline along the east side of the Sierra de la Nariz. The cones are shown at the margins of the basin-center lakebed-clay deposits and expand toward the outflow point (fig. 20). Cones north and south of the basin-center lakebed-clay deposits are independent of each other because of the barrier effect of the basin-center lakebed-clay deposits. Water-level declines were estimated to be as much as 20 ft at Papago Farms and more than 40 ft at the Mexican farms in December 1991. Simulated water levels in 1991 for five observation wells near Papago Farms are shown in figure 19.

If the conditions that existed in 1981 were constant for 10 years, as simulated in the model, storage would contribute more than 82 percent of the water pumped, which is about 3.0 percent of the water stored in the upper 400 ft of the aquifer. The remaining 18 percent would be contributed by inflow.

EXPLANATION

SPECIFIC YIELD, IN PERCENT

0.04-0.06

0.06-0.09

0.09-0.12

BOUNDARY OF MODELED AREA

BOUNDARY OF STUDY AREA

Figure 21. Continued.

SUMMARY

This water-resources study was undertaken to define and evaluate the availability and quality of surface water and ground water in the Papago Farms-Great Plain and upper Rio Sonoyta study area. Geohydrologic properties of the aquifer system were defined as part of the study. Ground water is the main source of water for irrigation and public supply in the study area because streamflow is not a dependable source of supply.

The study area is a 490-square-mile area that receives only about 5 to 8 in./yr of precipitation on the desert floor. Because the climate is semiarid to arid, most of the precipitation evaporates or is transpired by plants. The area is drained by the Rio Sonoyta and its main tributaries—the San Simon and Chukut Kuk Washes. Mean annual surface flow entering the area is estimated to be about 11,000 acre-ft, and another 3,000 acre-ft of runoff originates within the area. Surface-water runoff generally occurs as short-term flood events and does not constitute a reliable water supply.

The study area comprises two distinct topographic features—low jagged basin-boundary mountains and the broad, intermontane desert floor or flood plain. These features are the principal geologic units that control storage and flow of ground water in the aquifer system. The mountains extend to depth as stepped and faulted blocks, which form the boundary of the aquifer. The aquifer consists of sedimentary material that fills the basin between the mountains and hills and that overlaps the pediments and lower slopes; it is collectively referred to as basin fill. The basin fill consists of irregular, overlapping, and interfingering lenses of alluvial-fan, stream-channel, deltaic, and lakebed-clay deposits. The deposits generally grade from coarse sediments along the mountain fronts to massive beds of silty clay in the basin center.

Nearly all the recoverable ground water in the study area is in the basin fill. Saturated thickness of the basin fill ranges from zero near the margins to more than 8,000 ft in the center of the basin. The ground water occurs in the basin fill under unconfined conditions. Depth to water ranges from about 500 ft near the southern boundary of the study area to about 150 ft in the center.

Ground water moves into the area from the north and northeast through the basin fill beneath the San Simon and Chukut Kuk Washes and infiltrates along the mountain fronts within the area. The gradient of the water table is 70 ft/mi at Sierra del Cobre and 3 ft/mi in the vicinity of Papago Farms. Ground water moves through the study area along paths that encircle the virtually impermeable basin-center lakebed-clay deposits and moves westward to an outflow point beneath the Rio Sonoyta south of Cerro La Nariz. Rates of water movement range from less than 1 ft/yr in basin-center lakebed-clay deposits to about 160 ft/yr in well-sorted, coarse stream-channel deposits.

Transmissivity, which is directly proportional to the saturated thickness and hydraulic conductivity of the basin fill, is highly variable across the basin. Transmissivities along the basin margins range from 10,000 to 40,000 ft^2/d, whereas transmissivities in the basin-center lakebed-clay deposits are estimated to be less than 100 ft^2/d. In general, most wells that tap more than 300 ft of saturated basin fill in the upper 1,000 ft of the aquifer and are outside the zone of basin-center lakebed-clay deposits should yield from 500 to 3,000 gal/min to properly constructed and developed wells. Specific capacities should range from 10 to 50 (gal/min)/ft of drawdown.

The water in the aquifer is moderate to poor in chemical quality for irrigation and public-supply use. The ground water is principally a sodium bicarbonate type with dissolved-solids concentrations that range from 250 to 5,000 mg/L and average about 530 mg/L. The poorest quality water is associated with the basin-center lakebed-clay deposits. In much of the basin the water contains fluoride concentrations that exceed the maximum contaminant levels (primary limits) acceptable for drinking water. Water from the basin-center lakebed-clay deposits is also anomalously high in dissolved arsenic and is unacceptable for public supply. In parts of the study area, high concentrations of sodium and bicarbonate in the ground water present potential hazards to most crops. Use of this ground water for irrigation requires prudent farm-management practices.

The mean annual inflow to the aquifer from all infiltration and underflow was estimated from modeling to be about 4,400 acre-ft/yr. The amount of recoverable ground water in storage to a depth of 400 ft below the 1978-80 water table was estimated to be about 10 million acre-ft. Withdrawals from the aquifer in 1981 were estimated to be about 23,700 acre-ft. At the withdrawal rate of 1981, storage is being depleted by about 20,500 acre-ft/yr. The amount of storage depletion and drawdown of the water table on the basis of a mathematical simulation of the ground-water system and withdrawal rates in 1981 was projected to 1991. Water-level declines in 1991 were estimated to be as much as 20 ft at Papago Farms and more than 40 ft in the upper Rio Sonoyta area; however, the total decline represents a depletion of less than 3.0 percent of the ground water stored in the upper 400 ft of the aquifer. Ground-water withdrawals in the upper Rio Sonoyta area do not appear to have an effect on water levels in the Papago Farms-Great Plain area. The virtually impermeable basin-center lakebed-clay deposits act as a ground-water barrier between Papago Farms and irrigated areas to the south.

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CONVERSION FACTORS

For readers who prefer to use metric units, the conversion factors for the terms used in this report are listed below:

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.09290	square meter (m^2)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.405	square hectometer (hm^2)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile $(ft^3/s)/mi^2$	0.01093	cubic meter per second per square kilometer $(m^3/s)/km^2$
acre-foot per year per mile (acre-ft/yr)/mi	0.00077	cubic hectometer per year per kilometer $(hm^3/yr)/km$
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per minute per foot (gal/min)/ft	0.207	liter per second per meter (L/s)/m
ton per day (ton/d)	0.9072	megagram per day (mg/d)
micromho per centimeter (µmho/cm) at 25°C	1	microsiemen per centimeter (µS/cm) at 25°C

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level.

GPO 587-044/10023