UNITED STATES
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GEOLOGICAL SURVEY

SIMULATIVE MODELS FOR THE ANALYSIS OF GROUND-WATER FLOW IN VEKOL VALLEY, THE WATERMAN WASH AREA, AND THE BOSQUE AREA, MARICOPA AND PINAL COUNTIES, ARIZONA

By Daniel T. Matlock

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This copy of the report, which is printed on one side of the paper, is missing page numbers 8, 10, 14, 19, 22, 23, 26, 27, 30, 35, 38, 42, 46, 50, 51, 54, 59, 62, 66, 67, 70, and 74, because the backs of the figures were counted but not numbered. (See enclosed bound copy.)

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CONVERSION FACTORS

For readers who prefer to use the International System of Units (SI) rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

Multiply inch-pound unit	By	To obtain SI (metric) unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	0.4047	hectare (ha)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
degree Fahrenheit (°F)	(temp °F-32)/1.8	degree Celsius (°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."

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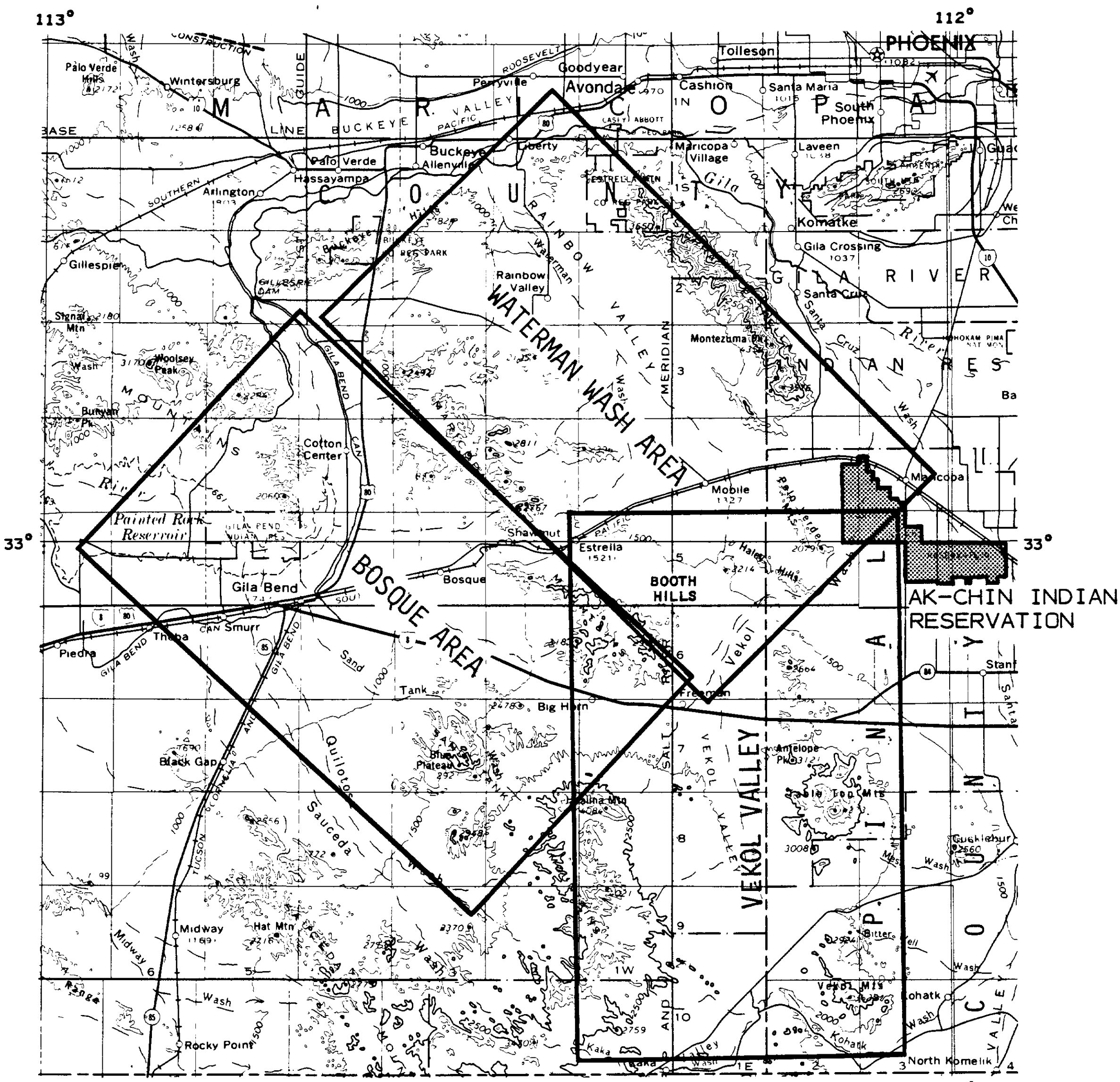
ABSTRACT

Simulative ground-water flow models for Vekol Valley, the Waterman Wash area, and the Bosque area were developed for use in evaluating alternatives for developing a ground-water supply for the Ak-Chin Indian Community. The hydraulic properties of the basin-fill deposits used in the models were estimated primarily from aquifer tests made by the U.S. Geological Survey. Annual recharge to Vekol Valley and the Waterman Wash area is negligible in comparison to the quantity of water in storage and the quantity proposed to be pumped. The models are based on a three-dimensional, block-centered, finite-difference scheme. The Vekol Valley model was calibrated for steady-state conditions, and the Waterman Wash area model was calibrated for steady-state and transient conditions. The sensitivity of calibrated heads to changes in transmissivity was also investigated. An uncalibrated storage-depletion model was developed for the Bosque area. Simulated water levels for steady-state conditions average within 5 feet of measured values for Vekol Valley and within 6 feet for the Waterman Wash area. Simulated water levels for transient conditions in the Waterman Wash area average within 8 feet of measured values for 15 years of analysis and within 15 feet for 24 years. Water-level declines simulated by the Waterman Wash area model average within 17 feet of those measured during the 24-year period, 1951-75.

INTRODUCTION

The Ak-Chin Indian Community Water Rights Settlement Act—Public Law 95-328—was enacted on July 28, 1978. The Act provides that 85,000 acre-ft/yr of water be supplied to meet the interim needs of the Ak-Chin Indian Community until a permanent source of water is found and a supply is made available—no more than 25 years after passage of the law. The U.S. Geological Survey was directed by the Secretary of the Interior to undertake hydrologic studies on nearby Federal land to determine if a sufficient ground-water supply is available. A report (Wilson, 1979) indicated that a sufficient quantity of ground water is available from alluvial aquifers that underlie Vekol Valley, the Waterman Wash area, and the Bosque area (fig. 1).

The Bureau of Indian Affairs was given lead responsibility for the planning, construction, and operation of the Ak-Chin Water Supply

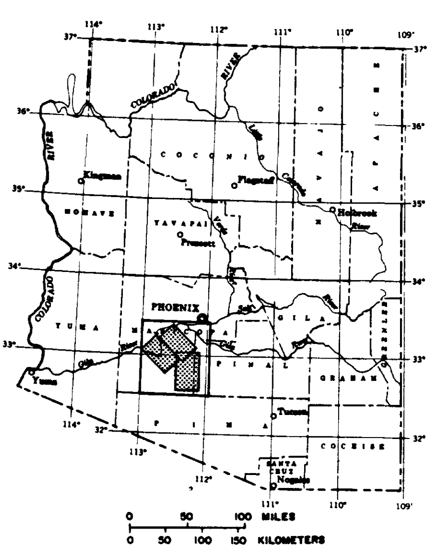


113° BASE FROM U.S. GEOLOGICAL SURVEY STATE TOPOGRAPHIC MAP, 1:500,000

0 10 20 MILES

0 10 20 KILOMETERS

CONTOUR INTERVAL 500 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929



INDEX MAP SHOWING AREA OF REPORT (SHADED)

Figure 1.--Area of report.

Project. After reviewing the impacts associated with the project, the Bureau determined that the project represents a major Federal action that requires an Environmental Impact Statement (EIS). The Bureau requested the U.S. Geological Survey to assist in the impact analysis by developing simulative ground-water flow models. The models will help fulfill the project requirements of an EIS and will aid in management decisions during well-field construction and operation.

Purpose and Scope

The purpose of this study was to develop simulative ground-water flow models that can be used as tools for evaluating alternatives for developing a ground-water supply for the Ak-Chin Indian Community. The models are the basic foundations for more refined versions that will provide management information on well-field design and operation, projection of land subsidence, and evaluation of impacts of the development. The use of a numerical model will (1) help to improve the understanding of the physical systems, (2) refine estimates of aquifer characteristics and flow components, and (3) serve as a guide for further data-collecting activities necessary to refine the models to represent the systems more accurately. The models represent simplified conceptual frameworks of complex hydrologic systems. At the present time (1981), the models provide the most accurate and practical way to predict the probable behavior of these systems to imposed stresses.

This report includes a discussion of the (1) numerical model and analyses applied in the study; (2) ground-water systems; (3) development of the simulation models; and (4) limitations, improvements, and possible future uses of the models.

Previous Investigations

Hydrologic studies by several investigators provided information for the development of ground-water models for the three areas. Wilson (1979) provided a summary of ground-water conditions in Vekol Valley and compiled ground-water data for the Waterman Wash and Bosque areas. Wilson's report describes the extent, thickness, and lithology of the water-bearing deposits and includes depth to water, well yields, and volume of recoverable ground water in storage for the three areas. White (1963) and Wolcott (1952) provided earlier summaries of ground-water conditions in the Waterman Wash area. These reports focus on the movement and occurrence of ground water, recharge and discharge relations, water levels, and hydraulic characteristics of the aquifers. Stulik and Moosburner (1969) provided specific-capacity data for the Bosque area. Studies by Babcock and Cushing (1942), Coates (1952), Coates and Cushman (1955), Johnson and Cahill (1954), Heindl and Armstrong (1963), and Denis (1968) also were helpful in evaluating the ground-water conditions in the three areas.

General Setting

Vekol Valley, the Waterman Wash area, and the Bosque area are structural depressions that are surrounded by mountains, which are composed of igneous, metamorphic, and sedimentary rocks. The main source of water in the three areas is the saturated basin-fill deposits, which consist mainly of unconsolidated to moderately consolidated sand, gravel, silt, and clay. Annual recharge to Vekol Valley and the Waterman Wash area is negligible in comparison to the quantity of water in storage and the quantity proposed to be pumped.

Vekol Valley is southwest of the Ak-Chin Indian Reservation in south-central Arizona (fig. 1). This north-trending valley is about 30 mi long, 5 to 10 mi wide, and is bounded by the Table Top and Vekol Mountains on the east, the Sand Tank and Maricopa Mountains on the west, (Wilson, 1979, p. 8) and the Booth and Haley Hills on the north. Vekol Wash, which drains most of the valley, flows northward and leaves the valley through a narrow gap between the Haley Hills and the Table Top Mountains.

The Waterman Wash area is northwest of the Ak-Chin Indian Reservation (fig. 1). This northwest-trending valley is about 30 mi long, 10 mi wide, and is bounded by the Buckeye Hills on the north, the Haley and Booth Hills and Palo Verde Mountains on the south, the Sierra Estrella on the east, and the Maricopa Mountains on the west (Wilson, 1979, p. 15-16). Waterman Wash flows northward and leaves the valley between the Buckeye Hills and the Sierra Estrella.

The Bosque area lies 41 mi west of the Ak-Chin Indian Reservation (fig. 1). The area is about 15 mi long, 2 to 10 mi wide, and is bounded by the Maricopa Mountains on the north and east, the Sand Tank Mountains on the south (Wilson, 1979, p. 21), and the Gila River on the west.

The three areas are arid, and average annual precipitation is estimated to be 7.5 in. (White, 1963). Maximum summer temperatures commonly exceed 100°F; minimum winter temperatures are seldom below 32°F (Sellers and Hill, 1974). The washes that drain the areas generally are dry and flow only in response to rainfall of high intensity or long duration.

Numerical Model

The numerical model used for this study is a three-dimensional block-centered finite-difference model developed by Trescott (1975, 1976). The computer code for the Trescott model will permit the hydrologic systems in the study areas to be represented as single-layer or multilayer systems. Vekol Valley is represented as one layer in the northern part of the valley and as two layers in the southern part. The Waterman Wash and Bosque areas are represented as one-layer systems. Because of the computer code used, more layers may be added to the analysis if and when additional data allow better three-dimensional definition of the existing flow systems. Subsidence-prediction capability also can be coupled to the Trescott model with the modifications developed by Meyer and Carr (1979). Minor alterations to the Trescott model, which were needed in the transient projections for Vekol Valley, are discussed in the section entitled "Projections Using the Vekol Valley Model."

The numerical model requires the area of interest to be divided into one or more layers of rectangular blocks. The center of each block is called a node. Each layer represents a vertical thickness of porous medium whose hydraulic properties may vary from node to node. The model computes heads and resultant flow between blocks due to imposed stresses by solving the ground-water flow equations over selected time increments during which the stresses are assumed to be constant.

The model uses a "leakage coefficient" to express the degree of hydraulic connection between layers in the system where more than one layer is defined. The leakage coefficient is equal to the vertical hydraulic conductivity divided by the distance through which flow occurs; thus, vertical rates of flow relate to differences in head between layers in the system. The leakage coefficient has units of reciprocal time.

The model computes transmissivity as a function of the hydraulic head in the upper layer where that layer of the system is unconfined. This allows the transmissivity to vary in proportion to the saturated thickness of the unconfined layer.

The model allows for two types of boundary conditions: constant flux and constant head. A constant-flux boundary is one at which the flow rate into or out of an active node remains constant in time. The flow rate can be zero or have a finite value. A constant-head boundary is one at which the hydraulic head remains constant in time for all rates of flow into or out of an active node.

Methods of Analysis

Simulation with a numerical model is usually done in two stages: steady state and transient. The steady-state model simulates equilibrium conditions where the amount of discharge from the system is in dynamic balance with the amount of recharge and no change of head occurs with time. The transient model simulates nonequilibrium conditions where stresses are imposed on the natural system that induce water-level changes with time.

Vekol Valley is assumed to be in a state of equilibrium. In the Waterman Wash area ground-water development began about 1951; consequently, steady-state and transient conditions can be analyzed. In the Bosque area water levels, stresses, and boundary conditions are not defined adequately to allow an analysis of steady-state or transient conditions. A storage-depletion model was developed that simulates only the amount of drawdown caused by the proposed withdrawals from an ambient condition. The model represents a simplified system that neglects any initial conditions or stresses that may exist.

The simulation of steady-state and transient conditions for Vekol Valley and the Waterman Wash area was accomplished through a process commonly referred to as "calibration." Calibration, as used in this study, is a trial-and-error procedure by which the initial estimates of input parameters and boundary conditions are adjusted until the difference between heads simulated by the model and those measured is less than an acceptable amount. Because measured heads can be duplicated by using unreasonable combinations of input parameters and boundary conditions, adjustments are restricted to values that are considered reasonable and within the limits of what is known about the system.

Calibration of the steady-state model provides improved estimates of input parameters, such as transmissivity, hydraulic conductivity, and leakage coefficients, as well as the boundary conditions. Calibration of the transient model, which uses the steady-state model parameters and boundary conditions as a starting point, establishes the additional nonequilibrium parameter of storage coefficient.

An analysis to determine the relative sensitivity of calibrated head values to changes in transmissivity was performed for the steady-state Vekol Valley model and the steady-state and transient Waterman Wash area models. The results of the analysis provide a useful guide for planning future field investigations.

In general, the sensitivity of gradients or heads to variations in the input parameter of transmissivity can be shown to be proportional to the specific discharge and inversely proportional to the transmissivity (Boggs, 1980). The procedure used to quantify these relations is as follows.

A number of zones of equal size and shape were selected for the modeled areas to provide a uniform distribution over the models with representation of all hydrogeologic conditions. A steady-state simulation was performed in which the transmissivities at all nodes within a zone were decreased by 50 percent, and the other model parameters—including transmissivities in other zones—and boundary conditions were held constant at their initially calibrated values. The weighted average head change or "sensitivity coefficient" (B_n) for all the zones was then computed by the equation

$$B_n = \frac{\sum_{i=1}^{K} h_i * A_i}{S_n}, \text{ for all } n = 1, 2 \ldots\ldots N \qquad (1)$$

where

h_i* is absolute value of the resulting head change at node i,

A_i is area of the cell associated with node i,

S_n is area of the subdomain associated with zone n,

K is number of nodes in zone n, and

N is total number of zones.

This produces N sensitivity coefficients each time the transmissivity is changed.

By repeating this procedure for each zone, an N by N set of sensitivity coefficients was tabulated into a sensitivity matrix. Because all zones are the same size and all transmissivities within the zones are modified by the same percentage, comparison of the magnitude of the sensitivity coefficients provides an indication of the relative sensitivity of heads to changes in transmissivity in various parts of the model. Zones in which a change in transmissivity produces the largest effect on heads throughout the model are the areas where accurate input is most essential for proper calibration of the model. Additional field data in these areas would help to improve the estimates of transmissivity. The procedure was repeated for the transient Waterman Wash area model with the exception that the absolute value of the resulting head change at node i (h_i*) was computed with reference to heads obtained from the calibrated transient model for spring 1966.

VEKOL VALLEY

Geohydrology

Vekol Valley is divided into a southern part and a northern part along a buried ridge of consolidated rocks (fig. 2). In the southern part of the valley, Wilson (1979, p. 8) divided the more than 2,000 ft of basin-fill deposits into four units. In descending order the units are: an upper gravel, a silt and clay, a lower gravel, and a conglomerate (fig. 2). The upper two units appear to be continuous over much of the southern part of the valley; however, the silt and clay unit is assumed to coalesce with coarser alluvial material near the mountain fronts and near the buried ridge. The lower gravel unit is absent in Vekol 1 test hole but is penetrated by Vekol 2 and Vekol 3 test holes. The conglomerate unit is penetrated by Vekol 1 and Vekol 3 but is absent in Vekol 2. The northern part of the valley contains at least 1,900 ft of basin-fill deposits, which consist of gravel, sand, silt, clay, and tuff (Wilson, 1979, p. 10).

Depth to water ranges from about 335 to about 600 ft below the land surface in the southern part of the valley and from about 150 to about 500 ft in the northern part (Wilson, 1979, p. 12). Ground-water development in Vekol Valley has been slight, and the system is assumed to be at steady state. Wells in the valley are used mainly for livestock and domestic purposes; in the northern part of the valley about 200 acre-ft/yr is used for irrigation.

Ground-water movement in the basin-fill deposits is from south to north. The available water-level data and the geologic framework indicate that ground water moves from the southern part of the valley to the northern part through the shallow alluvial deposits that cover the consolidated rocks of the buried ridge. Ground water probably discharges as underflow from Vekol Valley into two other ground-water systems. Some water may flow into the lower Santa Cruz basin through the narrow gap between Haley Hills and the Table Top Mountains, and some may flow into the Waterman Wash area through the narrow gap between Haley and Booth Hills (fig. 3). Sufficient data are not available to determine the rate of ground-water flow into these areas.

The distribution of hydraulic heads in Vekol Valley was described by Wilson (1979, p. 10 and fig. 6). In the southern part of the valley the hydraulic gradient averages less than 1 ft/mi. At the buried ridge, the hydraulic gradient increases rapidly to about 90 ft/mi as a result of the decrease in saturated thickness of the basin-fill deposits. In the northern part of the valley, the hydraulic gradient decreases to about 5 ft/mi.

Aquifer Characteristics

Aquifer tests made at three sites by the U.S. Geological Survey provide the only data on transmissivity and hydraulic conductivity for Vekol Valley. In the northern part of the valley a 6-day test was performed at Vekol 5, and in the southern part a 5-day test and a step-drawdown test were performed at Vekol 6 and Vekol 2, respectively (fig. 3). Observation wells were available near Vekol 5 and Vekol 6. The transmissivity values estimated from the tests were divided by the approximate length of casing open to the formation to obtain the hydraulic conductivity. The test holes were assumed to penetrate the entire aquifer. If only part of the aquifer is penetrated, vertical gradients will exist near the wells during pumping, and the actual values of transmissivity and hydraulic conductivity may be higher than those estimated. The results of the tests are given in table 1. No test was made to determine the hydraulic conductivity of the silt and clay unit; however, because of the abundance of clay, the hydraulic conductivity is assumed to be several orders of magnitude less than that of the lower gravel and conglomerate units. Although this unit probably transmits little water, it may act as an important source of water when the system is stressed.

In the southern part of the valley most of the ground water is assumed to be under confined conditions because water levels measured in the lower gravel unit generally are above the base of the silt and clay unit. Water will be released from storage in the area where water is under confined conditions during the early development period owing to

EXPLANATION

18	CONSTANT-FLUX RECHARGE NODE—Number, 18, is the recharge rate in acre-feet per year
286	CONSTANT-FLUX DISCHARGE NODE—Number, 286, is the discharge rate in acre-feet per year
	ZERO-TRANSMISSIVITY NODE
	CONSOLIDATED ROCKS
VEKOL 2 ●	TEST HOLE
———	BOUNDARY OF MODEL

Figure 3.--Grid system and distribution of boundary conditions for the steady-state Vekol Valley model.

Table 1.--Aquifer-test results for Vekol Valley

Test hole	Data analyzed	Analytical method[1]	Transmissivity, in feet squared per day	Saturated thickness, in feet	Hydraulic conductivity, in feet per day
Vekol 2	recovery—pumped well	Jacob	24,000	1,500	16.0
Vekol 5	recovery—observation well	Jacob	4,600	1,400	3.3
Do.	drawdown—observation well	Boulton	3,600	1,400	2.6
Vekol 6	recovery—observation well	Jacob	13,400	1,150	11.7
Do.	drawdown—observation well	Hantush	7,700	1,150	6.7

[1]Lohman (1972).

the expansion of water and the compression of the aquifer system. The nonrecoverable specific storage for the silt and clay unit is estimated to be 1×10^{-4} ft^{-1}, and the recoverable specific storage is estimated to be 5×10^{-6} ft^{-1}. The specific storage for the lower gravel and conglomerate units is estimated to be 1×10^{-6} ft^{-1}. Near the mountain fronts and the buried ridge where the silt and clay unit pinches out and in the northern part of the valley, ground water is assumed to be under unconfined conditions. Water will be released from storage in the areas where water is unconfined primarily by dewatering of the basin-fill deposits. A reasonable value of specific yield to assume for use in the model would be between 0.10 to 0.15, which is of the same order of magnitude as that used for the Waterman Wash area (see section entitled "Transient Calibration and Results").

Recharge Estimates

The mountains that surround Vekol Valley are made up of consolidated rocks that prevent a significant amount of underflow from entering the valley. The most important source of ground-water recharge is infiltration of precipitation. The infiltration is assumed to occur mainly near the mountain fronts.

Estimates of mountain-front recharge in Vekol Valley are based on runoff and infiltration studies conducted in other basins in southern Arizona. Babcock and Cushing (1942) estimated that perhaps as much as 50 percent of the runoff from mountains is recharged to the ground-water reservoir at the mountain fronts. Coates and Cushman (1955) estimated that for the Douglas basin about 10 percent of the precipitation that falls on hardrock areas adjacent to the valley becomes runoff. The runoff value determined by Coates and Cushman (1955) may be high for Vekol Valley because of the differences in altitude and terrain of the two areas; consequently, their percentage will provide an upper bound for recharge estimates.

On the basis of a total mountain area of about 57,000 acres tributary to Vekol Valley, an annual average rainfall of 7.5 in., and the recharge percentages, about 1,780 acre-ft of water is estimated to reach the ground-water reservoir each year along the mountain fronts.

Development of the Simulation Model

Layers and grid system.--Vekol Valley was modeled as two layers in the southern part of the valley and as one layer in the northern part (fig. 2). The top layer includes the silt and clay unit of Wilson (1979, p. 8) and the coarser alluvial material that exists at this horizon near the mountain fronts and the buried ridge. The bottom layer includes the lower gravel and conglomerate units of Wilson (1979, p. 8). The bottom layer, which is the primary transmitter of water in the southern part of the valley, thins to extinction at the buried ridge. Flow across the ridge and through the northern part is transmitted by a single layer. This layer is equivalent geologically to the basin-fill deposits in the northern part of the valley.

A two-layer system was used in the southern part of the valley because of the large differences in hydraulic characteristics of the two layers. The top layer is expected to act as an internal boundary, supplying water to the bottom layer when the system is stressed. It will also play an important role in the consolidation process and in any consequent land subsidence.

The saturated thickness of the top layer was modeled as about 200 ft. The saturated thickness of the bottom layer in the southern part of the valley and the single layer in the northern part conform to the saturated-thickness map prepared by Wilson (1979, fig. 5). The maximum saturated thickness was limited to less than 1,600 ft.

The grid system consists of 15 rows and 34 columns (fig. 3). A grid spacing of 1 mi was used over most of Vekol Valley. The spacing of columns near the outflow and the buried ridge areas of the valley was reduced to 0.5 mi. The largest hydraulic gradients are in the areas where the saturated thickness and transmissivity are minimal (fig. 2). A finer grid spacing enhances the approximation of the gradients by the numerical models.

Input parameters and boundary conditions.--The input parameters required for the simulation of steady-state conditions include hydraulic conductivity for the top layer in the southern part of the valley and the single layer in the northern part, transmissivity for the bottom layer, leakage coefficients, and boundary conditions.

The initial estimate of hydraulic conductivity for the silt and clay unit, which is within the top layer, is based on a value of 4.3×10^{-2} ft/d for a similar material (Todd, 1959). The hydraulic conductivity for the top layer was increased near the mountain fronts where the fine-grained material is assumed to coalesce with coarser alluvium. The hydraulic conductivity used initially for the single layer in the northern part of the valley was based on the test results of Vekol 5. The ratio of horizontal to vertical hydraulic conductivity is not known; therefore, an estimate of 10:1 was used.

The initial estimates of transmissivity for the bottom layer were based on an average hydraulic-conductivity value of 11.4 ft/d, which was obtained from the test results of Vekol 2 and Vekol 6. Transmissivity values were distributed as a product of the saturated thickness of this layer (Wilson, 1979) and the average hydraulic conductivity.

The initial estimates of leakage coefficients used to connect the two layers in the southern part of the valley were computed as the vertical hydraulic conductivity of the top layer divided by its saturated thickness.

Inflow of water adjacent to mountain fronts was simulated with constant-flux boundary conditions. The recharge estimate of 1,780 acre-ft/yr was used as an upper bound for inflow. Outflow of water at the north end of the valley was simulated by constant-head boundary conditions. These boundaries were used to estimate lateral outflow rates and were converted to constant-flux boundaries after calibration.

Steady-state calibration and results.--The calibration of the steady-state model consisted of adjusting the initial estimates of model parameters until an acceptable fit was obtained between simulated and measured water levels in Vekol Valley. The hydraulic conductivity and transmissivity were fixed in areas where they were well defined by aquifer tests. Adjustments were made primarily to the magnitude and distribution of mountain-front recharge and hydraulic conductivity near the buried ridge and outflow area. Minor adjustments also were made to the initial estimates of the leakage coefficient and transmissivity.

The distribution of hydraulic conductivity for the top layer is shown in figure 4. The steady-state model appears to be most sensitive to values of hydraulic conductivity at the buried ridge.

The distribution of transmissivity for the model is shown in figure 5. Because the hydraulic conductivity of the top layer in the southern part of the valley is much smaller than that of the bottom layer, figure 5 represents the transmissivity for the bottom layer in this area. The transmissivity for the northern part of the valley represents the product of hydraulic conductivity and the saturated thickness of the single layer.

The leakage coefficients used to connect the two layers in the southern part of the valley range from 2.5×10^{-10} to 5.0×10^{-8} sec^{-1}. These values increase toward the periphery of the valley reflecting the more permeable material that appears to exist in these areas. The steady-state regime is sensitive to the magnitude of the leakage coefficients near the recharge areas and on the south side of the buried ridge where vertical gradients are present. A transient regime will induce vertical gradients over much of the southern part of the valley, and the model will be highly sensitive to the magnitude of the leakage coefficients. Thus, a refinement of these values will be necessary as more data on the vertical hydraulic conductivity of the silt and clay unit become available.

The distribution of boundary fluxes for the steady-state model is shown in figure 3. Total flux through the system amounted to about 870 acre-ft/yr, of which about 370 acre-ft/yr originated in the southern part of the valley and 500 acre-ft/yr in the northern part.

The simulated head distribution for the steady-state model is shown in figure 6. The average difference between the simulated and

EXPLANATION

HYDRAULIC CONDUCTIVITY IN FEET PER DAY

0.04-0.43

0.44-4.30

4.31-12.30

CONSOLIDATED ROCKS

BOUNDARY OF MODEL

Figure 4.--Distribution of hydraulic conductivity determined from the steady-state Vekol Valley model—top layer in southern part of the valley, single layer in northern part.

EXPLANATION

——— 8000 ——— APPROXIMATE LINE OF EQUAL TRANSMISSIVITY—Interval 2,000 feet squared per day

4 SENSITIVITY ZONE AND ZONE NUMBER

CONSOLIDATED ROCKS

VEKOL 2 ● TEST HOLE

BOUNDARY OF MODEL

Figure 5.--Distribution of transmissivity determined from the steady-state Vekol Valley model and location of sensitivity zones.

EXPLANATION

—— 1420 —— SIMULATED POTENTIOMETRIC CONTOUR—Shows water-level altitude simulated by the steady-state model. Contour interval 20 and 40 feet. National Geodetic Vertical Datum of 1929

● 1614/1617 WELL IN WHICH WATER LEVEL WAS MEASURED—First number, 1614, is measured water-level altitude. Second number, 1617, is simulated water-level altitude. National Geodetic Vertical Datum of 1929

CONSOLIDATED ROCKS

BOUNDARY OF MODEL

Figure 6.--Comparison of simulated and measured water levels for the steady-state Vekol Valley model.

measured water levels at 21 points in Vekol Valley is about 5 ft. The heads for both layers in the southern part of the valley are about the same. Vertical gradients are present at only a few nodes on the south side of the buried ridge. In this area only about 14 ft of head difference is required to move water from the bottom layer into the top layer.

Transmissivity sensitivity analysis.--Ten zones that measure 3 by 3 mi were selected within the Vekol Valley grid system for transmissivity sensitivity analysis (fig. 5). The procedure discussed in the section entitled "Methods of Analysis" was used with the exception that the transmissivities in zone 5 were reduced by only 25 percent to avoid convergence problems associated with the numerical model's approximation of the steep hydraulic gradient at the buried ridge. The resultant sensitivity matrix is shown in table 2.

The steady-state model is most sensitive to changes in transmissivity at the buried ridge—zone 5—and to a lesser degree in the northern part of the valley—zones 1-4. The model shows little sensitivity to changes in transmissivity in the southern part of the valley.

The magnitude of the sensitivity coefficients appears to be primarily a function of the specific discharge. In the southern part of the valley the specific discharge is low because a relatively small quantity of water moves through a large cross-sectional area. At the buried ridge, the specific discharge increases significantly as a result of a decrease in cross-sectional area. In the northern part of the valley the quantity of ground water that flows through the system progressively increases as more recharge is introduced. Although the specific discharge in the northern part is smaller than that at the buried ridge, it is still much higher than that in the southern part of the valley.

The sensitivity analysis indicates that useful information for future calibration could be obtained from aquifer tests performed in areas where heads are most sensitive to changes in transmissivity, such as near the buried ridge and at other points in the northern part of the valley.

THE WATERMAN WASH AREA

Geohydrology

Wilson (1979, p. 16) divided the more than 2,000 ft of basin-fill deposits in the Waterman Wash area into an upper and a lower unit. The upper unit consists of unconsolidated sandy clay to sand and gravel, and the lower unit consists of moderately consolidated sandy gravel to sand and gravel that contains small amounts of silt and clay. In this study no effort is made to distinguish separable units in the Waterman Wash area. Drillers' logs indicate that in general a higher percentage of gravel is present in the western and northwestern parts of the area and a higher

Table 2.--Sensitivity matrix for the steady-state Vekol Valley model

Zone	Sensitivity coefficient, in feet									
	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	B_{10}
1	9.99	0.20	0.12	0.01	0.03	0.0	0.06	0.05	0.06	0.05
2	2.19	1.39	.56	.89	.59	.01	.01	.01	.01	.02
3	5.39	1.93	2.18	1.53	1.22	.06	.05	.05	.04	.04
4	3.01	2.82	2.91	1.47	1.44	.20	.19	.18	.18	.18
5	41.87	39.51	39.68	39.22	21.06	7.62	7.61	7.62	7.62	7.61
6	.05	.07	.08	.14	.73	.33	.04	.13	.07	.06
7	.06	.07	.07	.08	.13	.24	.36	.17	.18	.12
8	.07	.07	.08	.08	.15	.30	.17	.13	.08	.14
9	.01	.01	.01	.01	.01	.02	.01	.01	.40	.01
10	.01	.01	.01	.02	.04	.10	.09	.11	.08	.28

percentage of clay is present in the central part. Depth to water ranges from less than 300 ft in the northwestern part of the area to more than 400 ft southwest of Mobil (Wilson, 1979, p. 18).

Ground-water pumpage for 1950-74 is shown in figure 7. The amount of pumpage for 1950 is a revision from that previously published (Babcock, 1977). The original estimate of 5,000 acre-ft is assumed to be in error. A review of the records indicates that no land was under cultivation prior to 1951 and no irrigation wells were installed until the latter part of 1950. Stock wells could not have withdrawn more than 100 acre-ft/yr. Thus, the system is assumed to have remained in a state of equilibrium until 1951.

Under equilibrium conditions, ground water that originated along the mountain fronts moved generally northward to an outflow point near the Buckeye Hills where Waterman Wash leaves the area (fig. 8). Ground water probably was discharged from the basin by evapotranspiration and as underflow (Wolcott, 1952; White, 1963). The hydraulic gradient at equilibrium averaged about 2 ft/mi. The development of ground water for agriculture after 1950 caused a cone of depression in the northwestern part of the valley that created a ground-water divide near the outflow area. Water-level declines of as much as 175 ft were observed from 1952-75.

Aquifer Characteristics

Estimates of transmissivity for the basin-fill deposits of the Waterman Wash area were made from an aquifer test and specific-capacity data. A transmissivity of 11,000 ft^2/d was obtained from a 5-day aquifer test made by the U.S. Geological Survey (Wilson, 1979, p. 18) at Waterman 3 test hole (fig. 8). Analysis of specific-capacity data by White (1963) at seven wells in the northwestern part of the area provided rough estimates of transmissivity that range from 4,000 to 12,700 ft^2/d. A hydraulic conductivity of 8.3 ft/d, which was estimated from the results of the aquifer test, is assumed to be representative of the system.

Ground water in the Waterman Wash area generally is unconfined. The specific yield for the upper 800 ft of the system was estimated by White (1963) to be about 0.12.

Recharge Estimates

The main sources of recharge to the Waterman Wash area are mountain-front recharge and possible underflow from Vekol Valley. White (1963), using the analysis of Babcock and Cushing (1942) and Coates and Cushman (1955), estimated that as much as 1,500 acre-ft/yr of water may recharge the system along the mountain fronts. White (1963) also suggested that some underflow may move into the system from Vekol

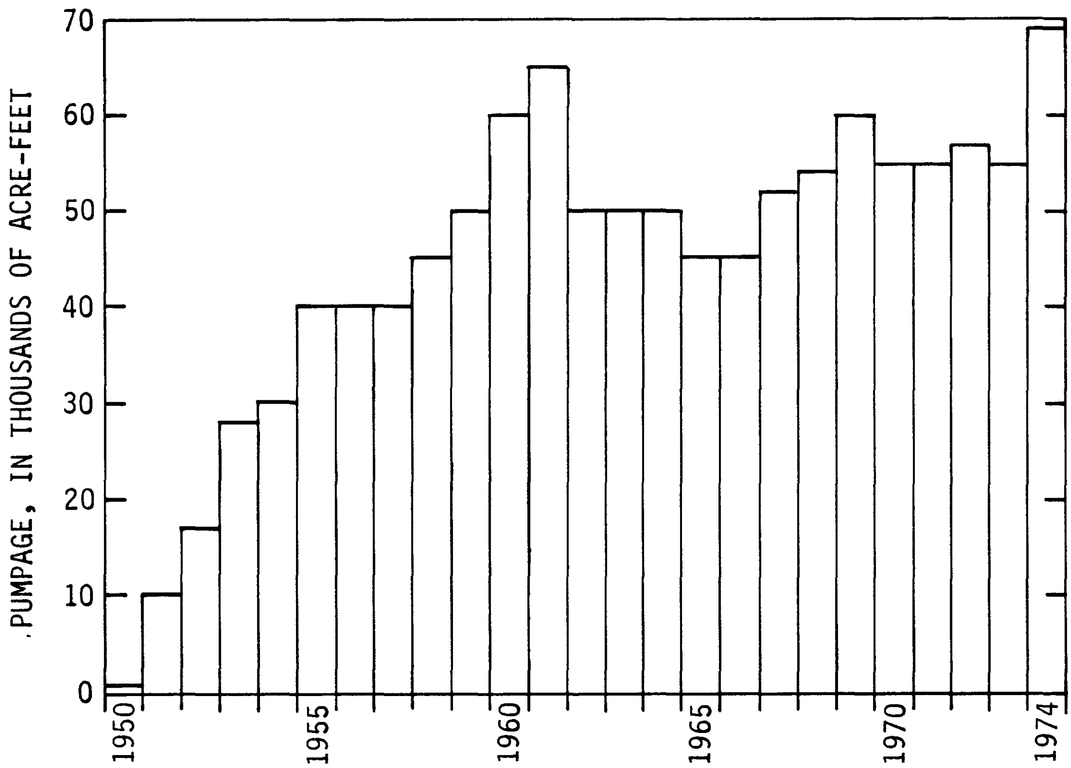


Figure 7.--Ground-water pumpage in the Waterman Wash area, 1950-74.
Data modified from Babcock (1977).

EXPLANATION

10	CONSTANT-FLUX RECHARGE NODE—Number, 10, is the recharge rate in acre-feet per year
1000	CONSTANT-FLUX DISCHARGE NODE—Number, 1,000, is the discharge rate in acre-feet per year
	ZERO-TRANSMISSIVITY NODE
	CONSOLIDATED ROCKS
WATERMAN 3 ●	TEST HOLE
———	BOUNDARY OF MODEL

Figure 8.--Grid system and distribution of boundary conditions for the steady-state Waterman Wash area model.

Valley between the Booth and Haley Hills. This amount, if any, would be small. The simulated outflow from Vekol Valley into the lower Santa Cruz and Waterman Wash areas is about 870 acre-ft/yr (fig. 3). Although the Vekol Valley model does not indicate the quantity that moves into each system, no more than 500 acre-ft/yr is assumed to discharge into the Waterman Wash area. The total amount of recharge to the Waterman Wash area was estimated to be about 2,000 acre-ft/yr.

Development of the Simulation Model

Grid system.--The modeled area consists of one layer, which is divided into 14 rows and 27 columns (fig. 8). A grid spacing of 1 mi was used over the entire Waterman Wash study area. The thickness of the single layer is based on the saturated-thickness map by Wilson (1979). The maximum saturated thickness was limited to less than 1,750 ft.

Hydraulic conductivity and boundary conditions.--The initial estimate of hydraulic conductivity used in the model is based on the results of the aquifer test at Waterman 3 (Wilson, 1979). Because information on the variation of hydraulic conductivity within the system was sparse, a constant value of 8.3 ft/d was assigned to all nodes.

Inflow of water along the mountain fronts and from Vekol Valley was simulated using constant-flux boundary conditions. The estimated mountain-front recharge of 1,500 acre-ft/yr was distributed along boundary nodes adjacent to runoff areas. To account for the inflow of water from Vekol Valley, 500 acre-ft/yr of additional constant-flux recharge was distributed over the southernmost boundary nodes of the model. The total steady-state recharge of 2,000 acre-ft/yr was placed in balance with the discharge by distributing constant-flux discharge near the Buckeye Hills where all equilibrium outflow is assumed to have occurred. The distribution of boundary conditions is shown in figure 8.

Steady-state calibration and results.--Calibration of the steady-state model was accomplished by fixing the boundary conditions and adjusting only the values of hydraulic conductivity. The hydraulic conductivity was increased in the western and northwestern parts of the area relative to that used in the area of the aquifer test to obtain an acceptable fit between simulated and measured water levels. Increasing the hydraulic conductivity in these areas is consistent with the observation that the basin-fill deposits contain less clay and more gravel and appear to be more permeable than the deposits in the area of the aquifer test. The hydraulic conductivity obtained from the calibration ranged from 8.3 to 16.6 ft/d. Transmissivity for the system is shown in figure 9.

EXPLANATION

12,000	APPROXIMATE LINE OF EQUAL TRANSMISSIVITY—Interval, 4,000 feet squared per day
5	SENSITIVITY ZONE AND ZONE NUMBER
	CONSOLIDATED ROCKS
WATERMAN 3	TEST HOLE
	BOUNDARY OF MODEL

Figure 9.--Distribution of transmissivity determined from the steady-state Waterman Wash area model and location of sensitivity zones.

The simulated head distribution for the steady-state model is shown in figure 10. The average difference between simulated and measured water levels at 12 points within the system is about 6 ft.

Transient calibration and results.--After the steady-state Waterman Wash area model was calibrated, transient simulations for two periods were performed to calibrate a specific-yield value for the system. The simulation for the first period, 1951-66, provided two reasonable values—0.11 and 0.12—of specific yield. The simulation for the second period, 1966-75, indicated that the best long-term value for specific yield is 0.12. Reconnaissance field studies made in spring 1966 and spring 1975 permitted a comparison of simulated and measured water levels. Monitoring of selected wells in the area provided for a time-drawdown comparison.

The transient simulation required an assessment of the pumping stresses. A few simplifications were made for determining the amount and distribution of pumpage. In the real system, wells withdraw water at different rates and at various times during a year. For the purpose of distributing stresses in the model, all wells were assumed to withdraw water at a constant average rate throughout the year. The magnitude and distribution of these stresses were varied from year to year depending on the total annual pumpage and the number of irrigation wells that were present. The large grid spacing made it necessary in some cases to combine the discharges of more than one well at a node, and in some cases the discharge from wells was proportioned among more than one node. The amount of return flow from irrigation in excess of consumptive use was assumed to be negligible.

The mountain-front recharge was held constant for all transient simulations. The constant-flux discharge was set to zero because pumpage in excess of steady-state recharge is assumed to have reversed the gradients quickly and lowered water levels at the outflow point causing the already very thin saturated material to be dewatered.

Transient conditions were simulated from spring 1951 to spring 1966 using the steady-state parameters, recharge-boundary conditions, and a range of specific-yield values between 0.10 and 0.13. Specific-yield values of 0.11 and 0.12 both provide acceptable fits to measured water levels on the basis of the analysis of the mean, mean absolute, and root-mean-square differences at 42 points in the study area (table 3). Water-level contours simulated using a specific yield of 0.12 superimposed on measured water levels for spring 1966 are shown in figure 11.

Transient conditions were simulated from spring 1966 to spring 1975 using specific yields of 0.11 and 0.12. A specific yield of 0.12 provided the best fit to this additional period of simulation when using the same points and statistical measures as those used for the analysis for spring 1966 (table 3). Results of this simulation are shown in figure 12.

EXPLANATION

——— 910 ——— SIMULATED POTENTIOMETRIC CONTOUR—Shows water-level altitude simulated by the steady-state model. Contour interval 10 feet. National Geodetic Vertical Datum of 1929

● 898/893 WELL IN WHICH WATER LEVEL WAS MEASURED—First number, 898, is measured water-level altitude. Second number, 893, is simulated water-level altitude. National Geodetic Vertical Datum of 1929

CONSOLIDATED ROCKS

BOUNDARY OF MODEL

Figure 10.--Comparison of simulated and measured water levels for the steady-state Waterman Wash area model.

Table 3.--Average difference between measured and simulated water levels for transient simulations with the Waterman Wash area model

Year	Specific yield	Mean difference[1]	Mean absolute difference[2]	Root-mean-square difference[3]
1966	0.10	8.91	10.86	14.27
1966	.11	2.02	7.54	11.45
1966	.12	-3.45	7.83	11.59
1966	.13	-8.43	11.52	14.18
1975	.11	9.43	20.57	26.14
1975	.12	2.52	14.81	19.77

[1]The average difference between measured and simulated values using the sign (±) associated with each pair of values.

[2]The average absolute difference between measured and simulated values.

[3]The square root of the sum of the squares of the differences between measured and simulated values. This tends to emphasize the largest differences between measured and simulated values.

EXPLANATION

—— 840 —— SIMULATED POTENTIOMETRIC CONTOUR—Shows water-level altitude simulated by the transient model. Contour interval 20 feet. National Geodetic Vertical Datum of 1929

●885 WELL IN WHICH WATER LEVEL WAS MEASURED—Number, 885, is measured water-level altitude. National Geodetic Vertical Datum of 1929

CONSOLIDATED ROCKS

BOUNDARY OF MODEL

Figure 11.--Simulated and measured water levels for the transient Waterman Wash area model, spring 1966.

EXPLANATION

——— 780 ——— SIMULATED POTENTIOMETRIC CONTOUR—Shows water-level altitude simulated by the transient model. Contour interval 20 feet. National Geodetic Vertical Datum of 1929

● 859 WELL IN WHICH WATER LEVEL WAS MEASURED—Number, 859, is measured water-level altitude. National Geodetic Vertical Datum of 1929

CONSOLIDATED ROCKS

BOUNDARY OF MODEL

Figure 12.--Simulated and measured water levels for the transient Waterman Wash area model, spring 1975.

Hydrographs were developed for nine wells to observe the model's approximation of water-level declines during the 24-year transient period (fig. 13). The largest average difference between simulated and measured declines was about 17 ft, which was in NW¼NW¼SW¼ sec. 9, T. 2 S., R. 2 W., and the smallest average difference was about 3 ft, which was in SW¼SW¼SE¼ sec. 21, T. 3 S., R. 1 W.

Transmissivity sensitivity analysis.--Nine zones that measure 3 by 3 mi were selected within the Waterman Wash area grid system for transmissivity sensitivity analysis (fig. 9). The resultant sensitivity matrices for the steady-state analysis and the transient analysis are shown in tables 4 and 5, respectively.

The sensitivity coefficients for the steady-state Waterman Wash area model do not exhibit the areal contrasts that were observed for the steady-state Vekol Valley model. The areas that appear to be most sensitive to changes in transmissivity are zones 2 and 4. In all other zones, changes in transmissivity have either a larger local effect, as exemplified in zone 1, or a more moderate effect over the entire model, as exemplified in zone 6.

The sensitivity coefficients for the transient Waterman Wash area model do exhibit some contrast. The transient model appears to be more sensitive to changes in transmissivity in the northern part of the area—zones 1-5—than in the southern part—zones 6-9. The zones of highest sensitivity are associated with the pumping center where the highest specific discharge occurs during transient analysis.

The sensitivity analysis indicates that useful information for future calibration could be obtained from aquifer tests performed in zones 1-5. Improved estimates of transmissivity in these areas would enhance calibration of the steady-state and transient models. Because more water-level data are available for the nonequilibrium system, future calibration efforts should advisedly be performed with the transient model.

THE BOSQUE AREA

An uncalibrated storage-depletion model was developed for the Bosque area. The model parameters were not assessed through calibration but were defined on the basis of the best available information.

Estimates of transmissivity were obtained from an aquifer test and specific-capacity data. A transmissivity of 800 ft^2/d was estimated by Wilson (1979, p. 25) from step-drawdown tests at Bosque 3 test hole (fig. 14). Specific-capacity data (Stulik and Moosburner, 1969) indicate that the transmissivity is much higher near the Gila Bend Canal where transmissivities ranging from 3,700 to 20,700 ft^2/d were estimated. In general, transmissivity appears to be higher in the northern part of the Bosque area.

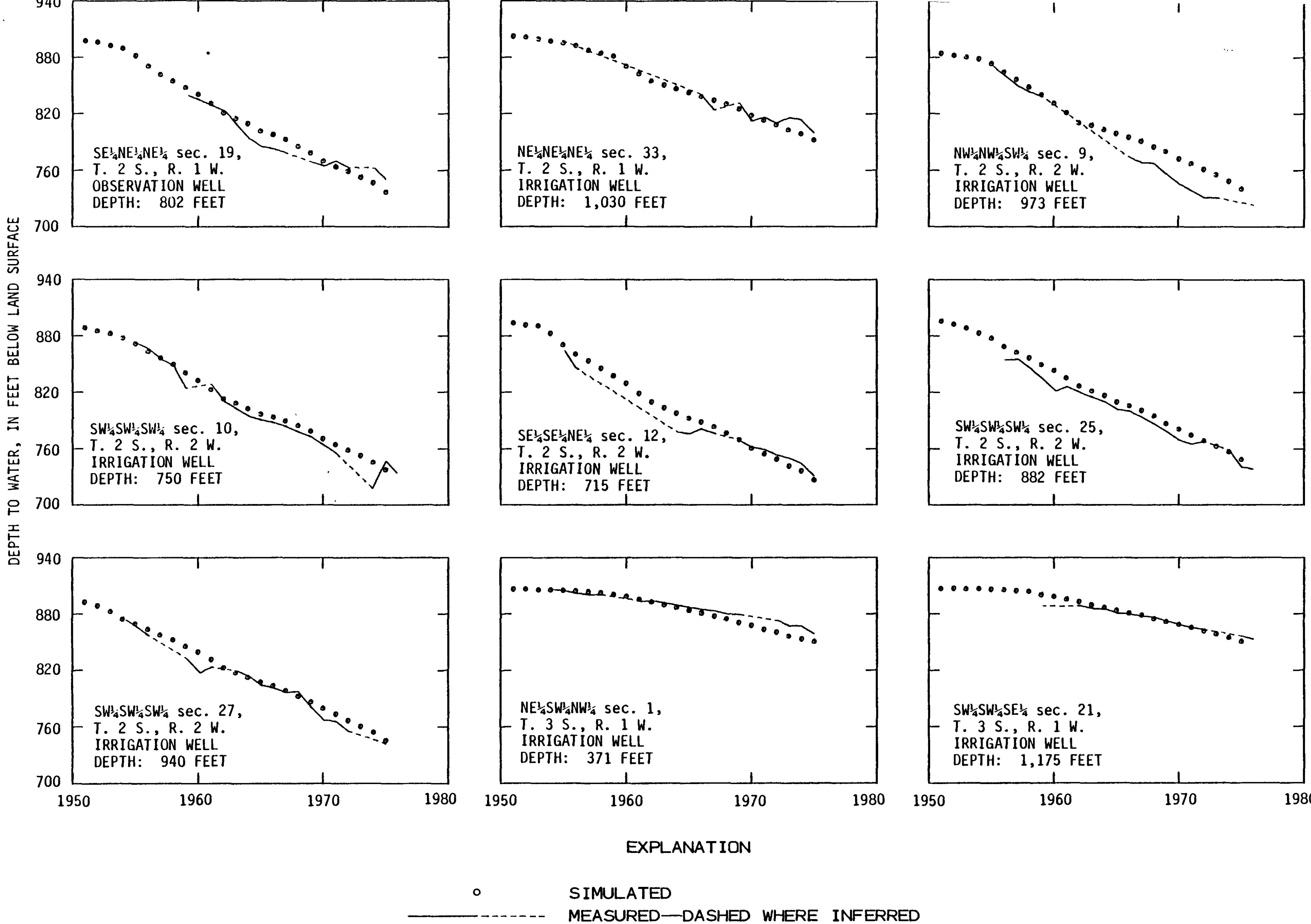


Figure 13.--Comparison of simulated and measured water levels for the transient Waterman Wash area model, 1951-75.

Table 4.--Sensitivity matrix for the steady-state Waterman Wash area model

Zone	Sensitivity coefficient, in feet								
	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
1	3.97	0.18	0.14	0.15	0.14	0.15	0.15	0.17	0.19
2	2.56	1.23	.78	.51	.12	.42	.31	.42	.42
3	1.68	.86	.76	.21	.70	.29	.38	.33	.32
4	2.04	2.16	1.77	.92	.45	.72	.43	.66	.64
5	.91	.80	1.08	.41	.61	.29	.61	.39	.37
6	.60	.60	.58	.65	.51	.73	.22	.71	.69
7	.49	.47	.51	.45	.60	.13	.46	.51	.47
8	.77	.76	.77	.76	.76	.72	.73	.98	2.18
9	.22	.22	.23	.22	.22	.20	.22	.26	1.30

Table 5.--Sensitivity matrix for the transient Waterman Wash area model

Zone	Sensitivity coefficient, in feet								
	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
1	5.16	0.85	1.46	0.34	0.30	0.02	0.04	0.00	0.00
2	.77	3.10	2.47	.57	.48	.19	.09	.07	.01
3	.16	.16	4.35	.51	.73	.18	.29	.07	0.00
4	2.80	4.57	4.17	4.89	1.77	3.10	1.88	.87	.08
5	1.43	1.83	4.04	1.37	6.01	.69	2.70	.40	.03
6	.16	.43	.35	1.24	.61	1.69	.41	.98	.13
7	.21	.46	.67	1.20	2.36	.26	3.00	.95	.09
8	.02	.01	.01	.11	.10	.67	.42	1.09	.49
9	.04	.05	.04	.03	.03	.06	.04	.40	.69

EXPLANATION

ZERO-TRANSMISSIVITY NODE

CONSOLIDATED ROCKS

BOSQUE 3 TEST HOLE

BOUNDARY OF MODEL

Figure 14.--Grid system for the Bosque area storage-depletion model.

The model consists of one layer, which is divided into 14 rows and 23 columns (fig. 14). A grid spacing of 1 mi was used over most of the Bosque study area. On two sides, the grid was expanded to place boundaries a sufficient distance from the center of proposed development. No-flow boundaries surround the system.

A constant saturated thickness of 1,000 ft was used for the single layer. The hydraulic-conductivity input to the model was obtained by dividing the transmissivity estimates by the saturated thickness. The sparse amount of information on the variation of transmissivity necessitated averaging hydraulic conductivity over large areas. The distribution of hydraulic conductivity is shown in figure 15.

Ground water in the Bosque area generally is unconfined (Paul Sebenik, Arizona Department of Water Resources, oral commun., 1980). The specific-yield value assumed for use in the model was of the same order of magnitude as that for the Waterman Wash area model, which was between 0.10 and 0.15.

PROJECTIONS USING THE VEKOL VALLEY MODEL

Vekol Valley was selected to illustrate the use of the models for evaluating impacts associated with the development of a ground-water supply for the Ak-Chin Indian Reservation. Two transient projections were made on the assumption that the full entitlement of water—85,000 acre-ft/yr—would be supplied from Vekol Valley for 25 years. The two projections contrast drawdowns resulting from a given distribution of pumpage for a probable range of aquifer storage.

The model by Trescott (1975, 1976) was modified to adjust the storage coefficient in the bottom layer and the leakage rate between layers in the southern part of the valley at time steps and nodes where the head in the bottom layer drops below the base of the top layer. The modifications allow (1) the storage coefficient to convert to specific yield and (2) the leakage rate, which is normally proportional to the difference in head between the two layers, to be proportional to the difference between the head and the bottom elevation of the top layer.

The well-field design used for the projections is shown in figure 16. Seventy-three wells were distributed between the southern (39) and northern (34) parts of the valley. The Papago Indian Reservation was assumed to be beyond the area of potential development; thus, all wells were located north of the reservation boundary. All wells were given a constant discharge rate of 720 gal/min for the 25-year period, and pumping in the southern part of the valley was confined to the bottom layer.

The mountain-front recharge was held constant at the calibrated steady-state levels. The outflow boundary at the north end of the valley

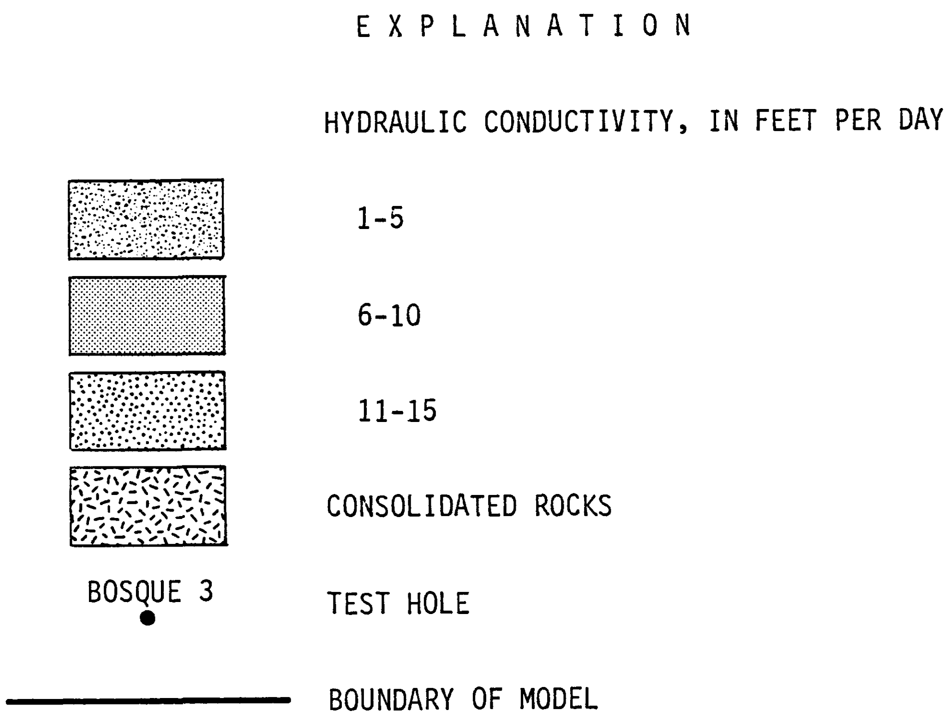


Figure 15.--Distribution of hydraulic conductivity for the Bosque area storage-depletion model.

E X P L A N A T I O N

STORAGE VALUES USED FOR THE PROJECTIONS

	Low values	High values
Specific yield	0.10	0.15
Storage coefficient	0.02	0.02
Storage coefficient	0.0001	0.001

● WELL LOCATION

CONSOLIDATED ROCKS

BOUNDARY OF MODEL

Figure 16.--Distribution of pumpage and aquifer storage for the Vekol Valley projections.

was converted to a no-flow boundary when the cone of depression reached this area.

The magnitude and distribution of storage coefficients and specific-yield values used in the two projections are shown in figure 16. The distribution of storage is based on those values discussed in the section entitled "Aquifer Characteristics." A nonrecoverable storage coefficient of 0.02 was used for the silt and clay unit. Storage coefficients of 0.001 and 0.0001 were used for the bottom layer in the southern part of the valley. Specific-yield values of 0.10 and 0.15 were used for the single layer in the northern part of the valley and in unconfined areas in the southern part of the valley.

The drawdowns for the projection with low values of storage are compared to the drawdowns for the projection with high values of storage in figure 17. Drawdowns are shown only for the bottom layer in the southern part of the valley. The contours of drawdown have the same general shape for both projections. The difference in drawdowns between the projections is about 50 ft in the southern part of the valley and about 75 ft in the northern part.

LIMITATIONS, IMPROVEMENTS, AND FUTURE USES OF THE MODELS

The models described in this report are useful tools for evaluating the ground-water flow systems of Vekol Valley, the Waterman Wash area, and the Bosque area. Various projections of the response in the systems to ground-water withdrawal can be made on a regional analysis. The models may be used to evaluate water-level declines that will result from different patterns and amounts of pumping for the Ak-Chin water supply and to separate the declines from those caused by existing users. As the data base is improved, the models may be refined and used to optimize the design and operation of a well field by coupling the ground-water flow models with an economic model. Subsidence analysis also may be coupled to the flow models as more information is obtained on the vertical hydraulic conductivity, compressibility, and thickness and extent of fine-grained units in these three systems.

The models provide only an approximation of the behavior of the real system, and caution should be exercised when using the models in their present state of development. The reliability of the models is limited, in general, by possible errors from (1) a lack of adequate input data including transmissivity, hydraulic conductivity, storage coefficient, pumpage distribution, specific yield, water levels, and boundary conditions; (2) inaccurate calibration; and (3) the numerical difficulties in representing a continuous three-dimensional flow system with a discrete two-dimensional or quasi three-dimensional model. The ability of the Vekol Valley and Bosque area models to predict aquifer response to imposed stresses or the Waterman Wash area model to simulate stresses that depart significantly from those under which it was calibrated is not known. The Waterman Wash area model should provide the most reliable

EXPLANATION

—— 150 —— CONTOUR OF PROJECTED DRAWDOWN FOR LOW VALUES OF STORAGE—Contour interval 25 and 100 feet

----- 150 ----- CONTOUR OF PROJECTED DRAWDOWN FOR HIGH VALUES OF STORAGE—Contour interval 25 and 100 feet

CONSOLIDATED ROCKS

BOUNDARY OF MODEL

Figure 17.--Drawdown comparison for the Vekol Valley projections.

results because calibration of the input parameters was performed for steady-state and transient conditions. The Vekol Valley model is less reliable than the Waterman Wash area model because calibration was performed for only steady-state conditions. The Bosque area model will provide the least reliable results because the input parameters were not assessed through calibration.

The most significant source of error appears to be inadequate data. The transmissivity and hydraulic-conductivity values used in the models are based on the results of only a few aquifer tests. The number and distribution of water-level measurements used for calibration were not adequate for the desired amount of control because a good knowledge of the head distribution provides the basis for reliable parameter estimation.

To improve the models, a network of exploratory wells would be helpful. The distribution of aquifer characteristics could be better estimated from the analysis of drill cuttings, core samples, geophysical logs, and aquifer tests. The wells also would provide an improved definition of the water levels. Transmissivity sensitivity analysis indicates that useful data for an improved calibration of the Vekol Valley model could be collected near the buried ridge and in the northern part of the valley. For the Waterman Wash area model, useful data could be collected in the area of the pumping center.

The models also may be improved through additional sensitivity analysis, such as the sensitivity of heads to changes in leakage coefficients and recharge rates. Future modeling efforts for the Waterman Wash area could be improved by using a more accurate distribution of pumpage and incorporating an analysis of return flows from irrigation, which was ignored in this study. Although the nature of the models and the general limitations preclude a precise evaluation of the response of the systems to imposed stresses, the models can provide effective tools for ground-water management if their reliability is improved by future refinements.

REFERENCES CITED

Babcock, H. M., 1977, Annual summary of ground-water conditions in Arizona, spring 1975 to spring 1976: U.S. Geological Survey Open-File Report 77-10, maps.

Babcock, H. M., and Cushing, E. M., 1942, Recharge to ground water from floods in a typical desert wash, Pinal County, Arizona: Transactions of the American Geophysical Union [23d annual meeting], pt. 1, p. 49-56.

Boggs, J. M., 1980, Impact of future ground-water development in Cienega Creek area, Pima, Santa Cruz, and Cochise Counties, Arizona: Tucson, University of Arizona, unpublished master's thesis, 131 p.

Coates, D. R., 1952, Gila Bend basin, Maricopa County, in Ground water in the Gila River basin and adjacent areas, Arizona—a summary, by L. C. Halpenny and others: U.S. Geological Survey open-file report, p. 159-164.

Coates, D. R., and Cushman, R. L., 1955, Geology and ground-water resources of the Douglas basin, Arizona, with a section on Chemical quality of the ground water, by J. L. Hatchett: U.S. Geological Survey Water-Supply Paper 1354, 56 p.

Denis, E. E., 1968, Ground-water conditions in the Waterman Wash area, Maricopa and Pinal Counties, Arizona: Arizona State Land Department Water-Resources Report 37, 23 p.

Heindl, L. A., and Armstrong, C. A., 1963, Geology and ground-water conditions in the Gila Bend Indian Reservation, Maricopa County, Arizona: U.S. Geological Survey Water-Supply Paper 1647-A, 48 p.

Johnson, P. W., and Cahill, J. M., 1954, Ground-water resources and geology of the Gila Bend and Dendora areas, Maricopa County, Arizona: U.S. Geological Survey open-file report, 53 p.

Lohman, S. W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Meyer, W. R., and Carr, J. E., 1979, A digital model for simulation of ground-water hydrology in the Houston area, Texas: Texas Department of Water Resources LP-103, 133 p.

Sellers, W. D., and Hill, R. H., eds., 1974, Arizona climate, 1931-1972: Tucson, Arizona University Press, 616 p.

Stulik, R. S., and Moosburner, Otto, 1969, Hydrologic conditions in the Gila Bend basin, Maricopa County, Arizona: Arizona State Land Department Water-Resources Report 39, 63 p.

Todd, D. K., 1959, Ground water hydrology: New York, John Wiley, 336 p.

Trescott, P. C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 103 p.

Trescott, P. C., and Larson, S. P., 1976, Documentation of finite-difference model for simulation of three-dimensional ground-water flow—supplement to Open-File Report 75-438: U.S. Geological Survey Open-File Report 76-591, 21 p.

White, N. D., 1963, Ground-water conditions in the Rainbow Valley and Waterman Wash areas, Maricopa and Pinal Counties, Arizona: U.S. Geological Survey Water-Supply Paper 1669-F, 50 p.

Wilson, R. P., 1979, Availability of ground water on Federal land near the Ak-Chin Indian Reservation, Arizona—a reconnaissance study: U.S. Geological Survey Open-File Report 79-1165, 36 p.

Wolcott, H. N., 1952, Rainbow Valley-Waterman Wash area, Maricopa County, in Ground water in the Gila River basin and adjacent areas, Arizona—a summary, by L. C. Halpenny and others: U.S. Geological Survey open-file report, p. 151-158.

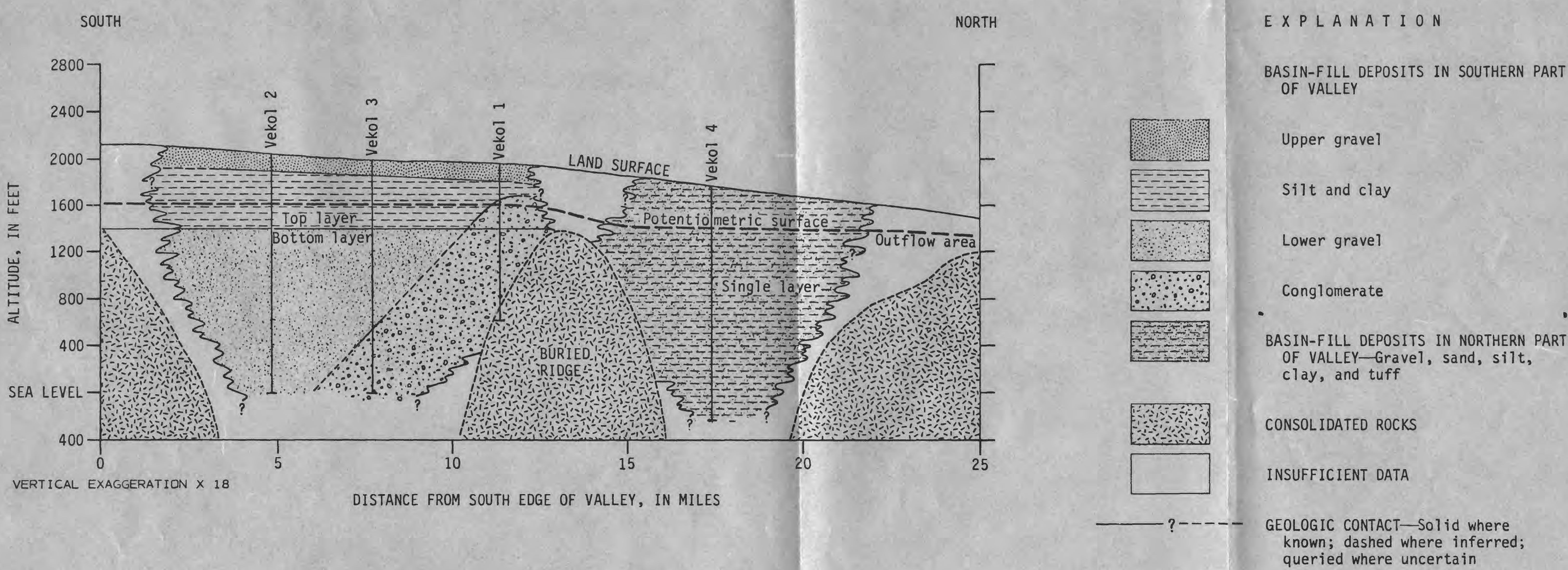
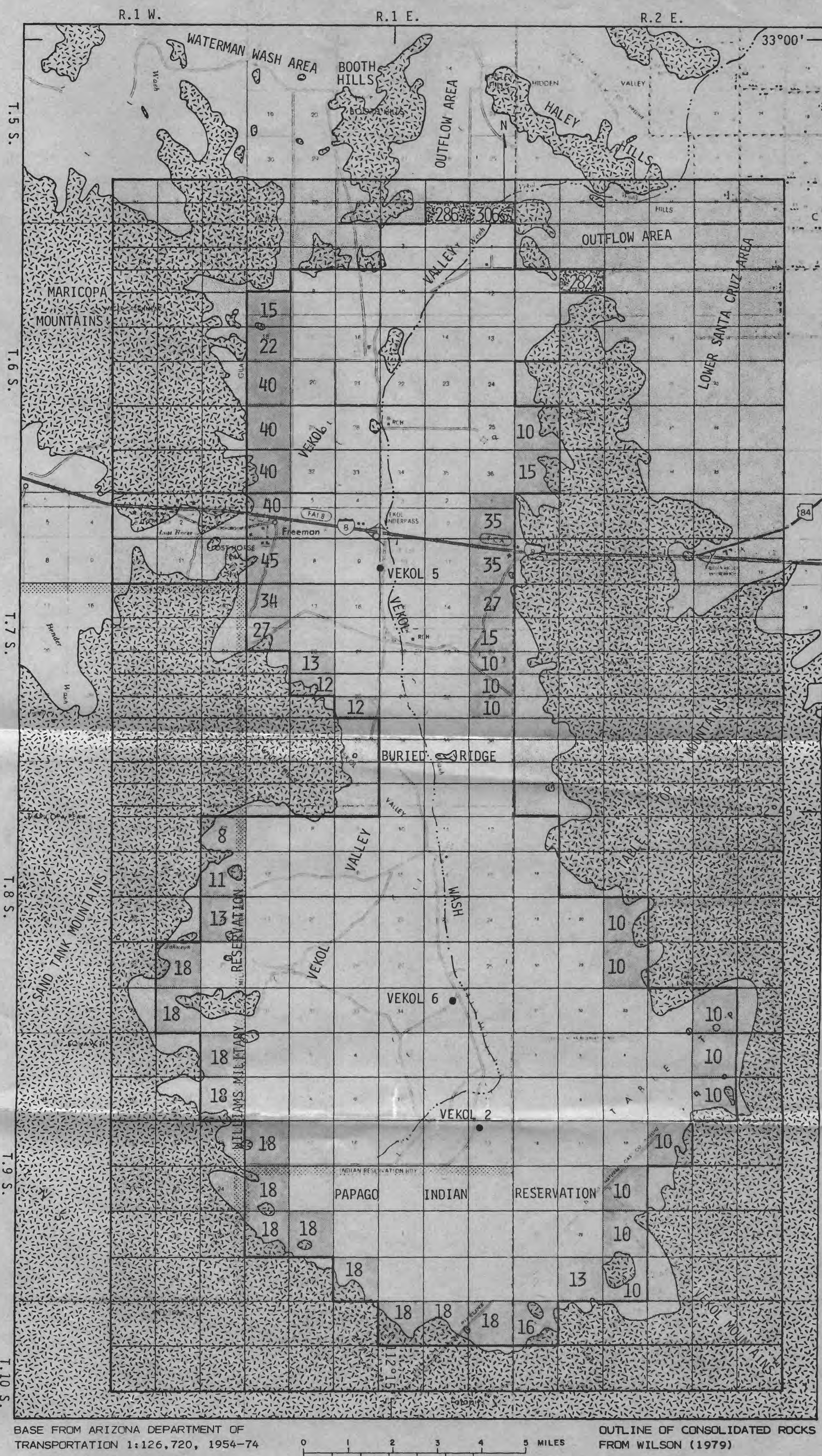


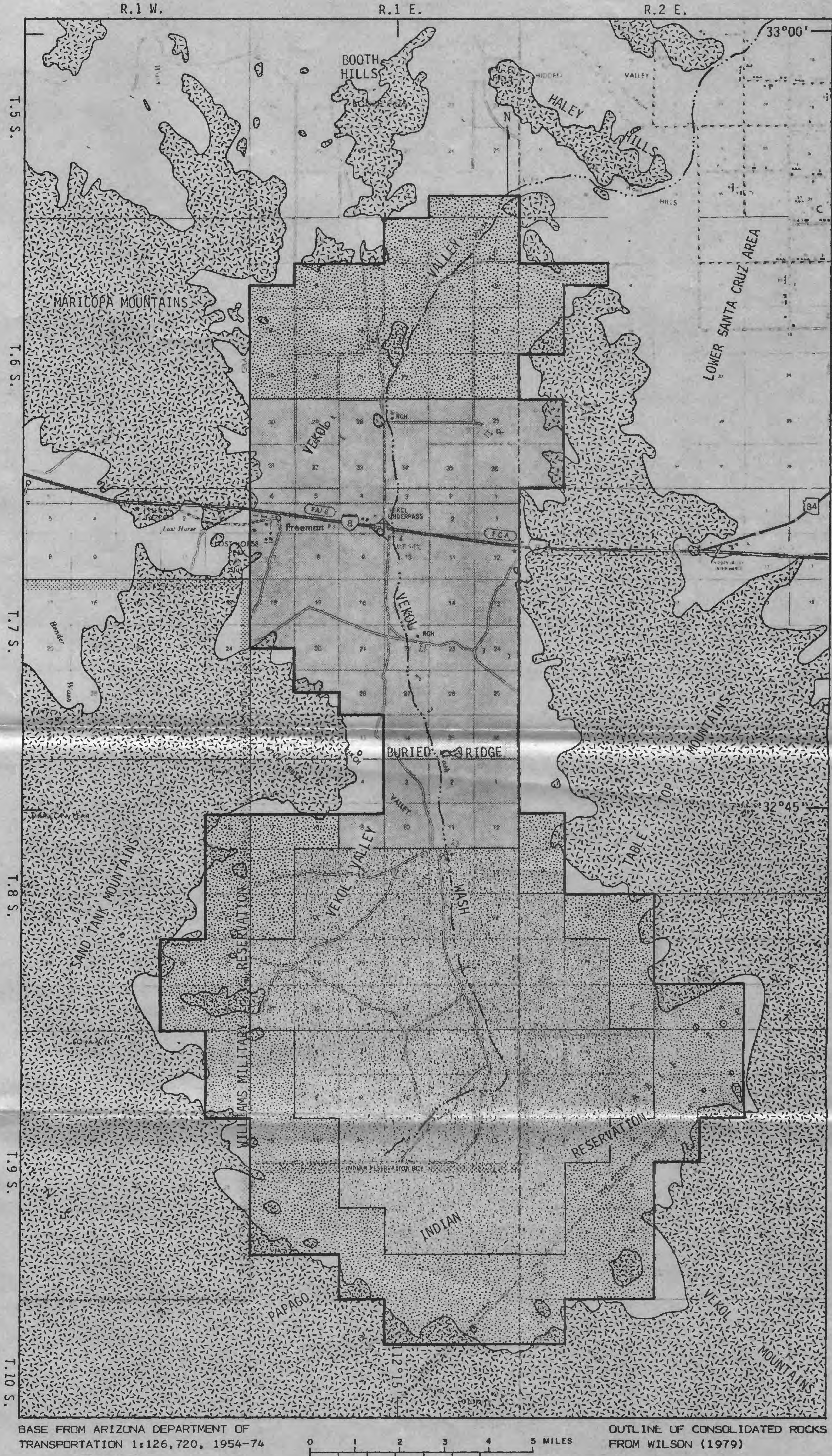
Figure 2.--Generalized profile of Vekol Valley showing relation between units described by Wilson (1979) and layers used in the model.



BASE FROM ARIZONA DEPARTMENT OF TRANSPORTATION 1:126,720, 1954-74

OUTLINE OF CONSOLIDATED ROCKS FROM WILSON (1979)

Figure 3

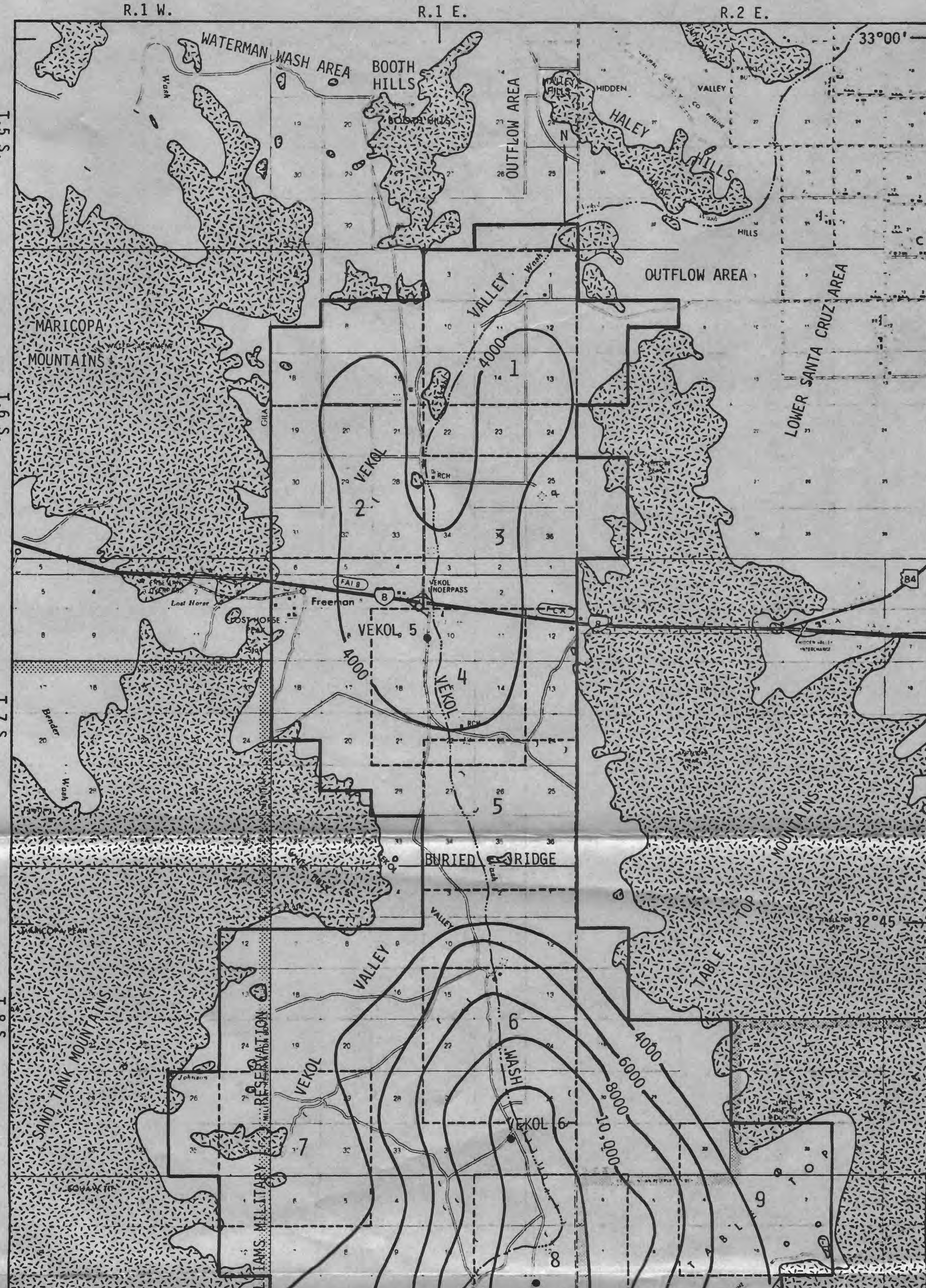


BASE FROM ARIZONA DEPARTMENT OF TRANSPORTATION 1:126,720, 1954-74

0 1 2 3 4 5 MILES
0 1 2 3 4 5 6 KILOMETERS

OUTLINE OF CONSOLIDATED ROCKS FROM WILSON (1979)

Figure 4

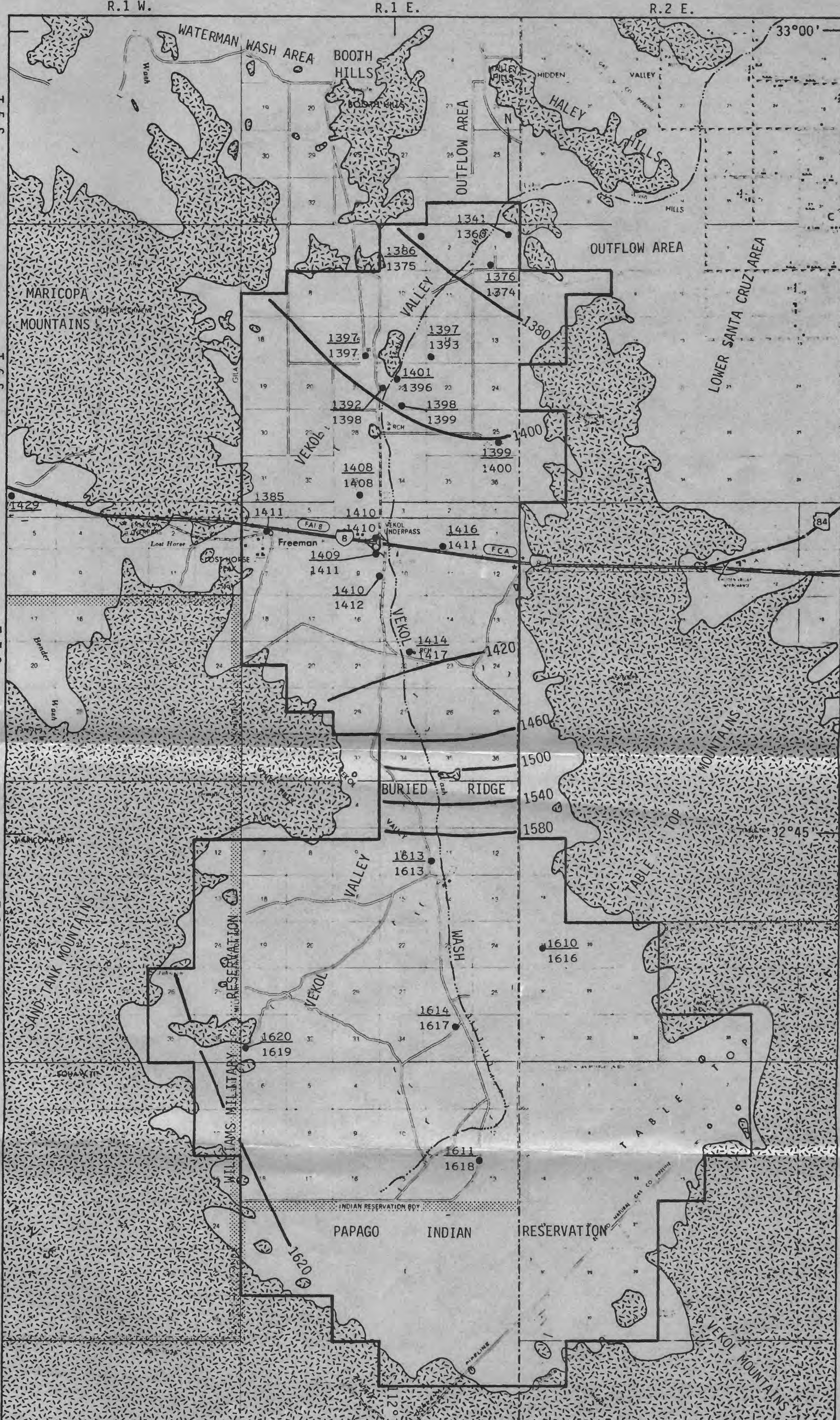


BASE FROM ARIZONA DEPARTMENT OF TRANSPORTATION 1:126,720, 1954-74

0 1 2 3 4 MILES
0 1 2 3 4 5 6 KILOMETERS

OUTLINE OF CONSOLIDATED ROCKS FROM WILSON (1979)

Figure 5

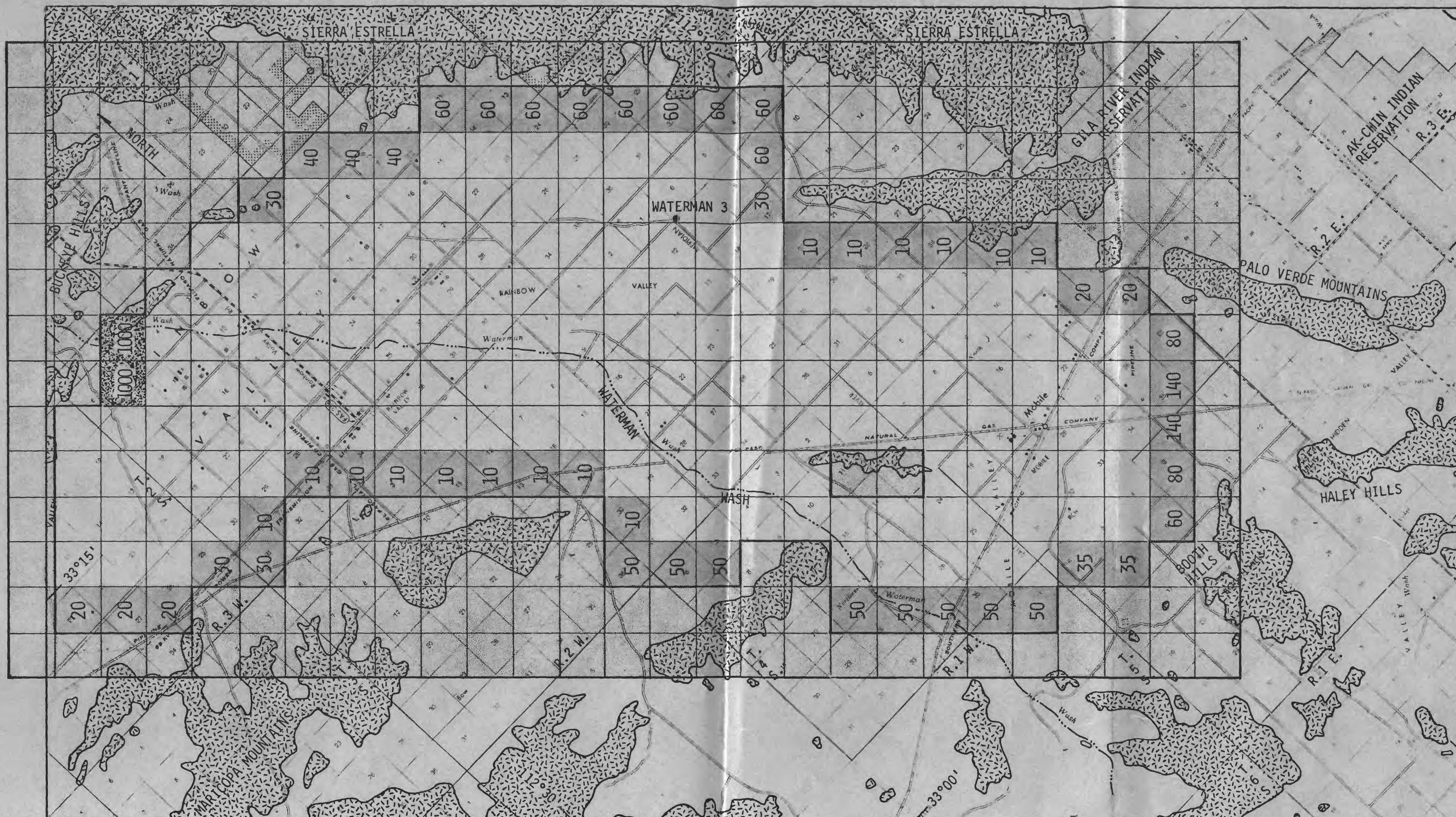


BASE FROM ARIZONA DEPARTMENT OF TRANSPORTATION 1:126,720, 1954-74

0 1 2 3 4 5 MILES
0 1 2 3 4 5 6 KILOMETERS

OUTLINE OF CONSOLIDATED ROCKS FROM WILSON (1979)

Figure 6



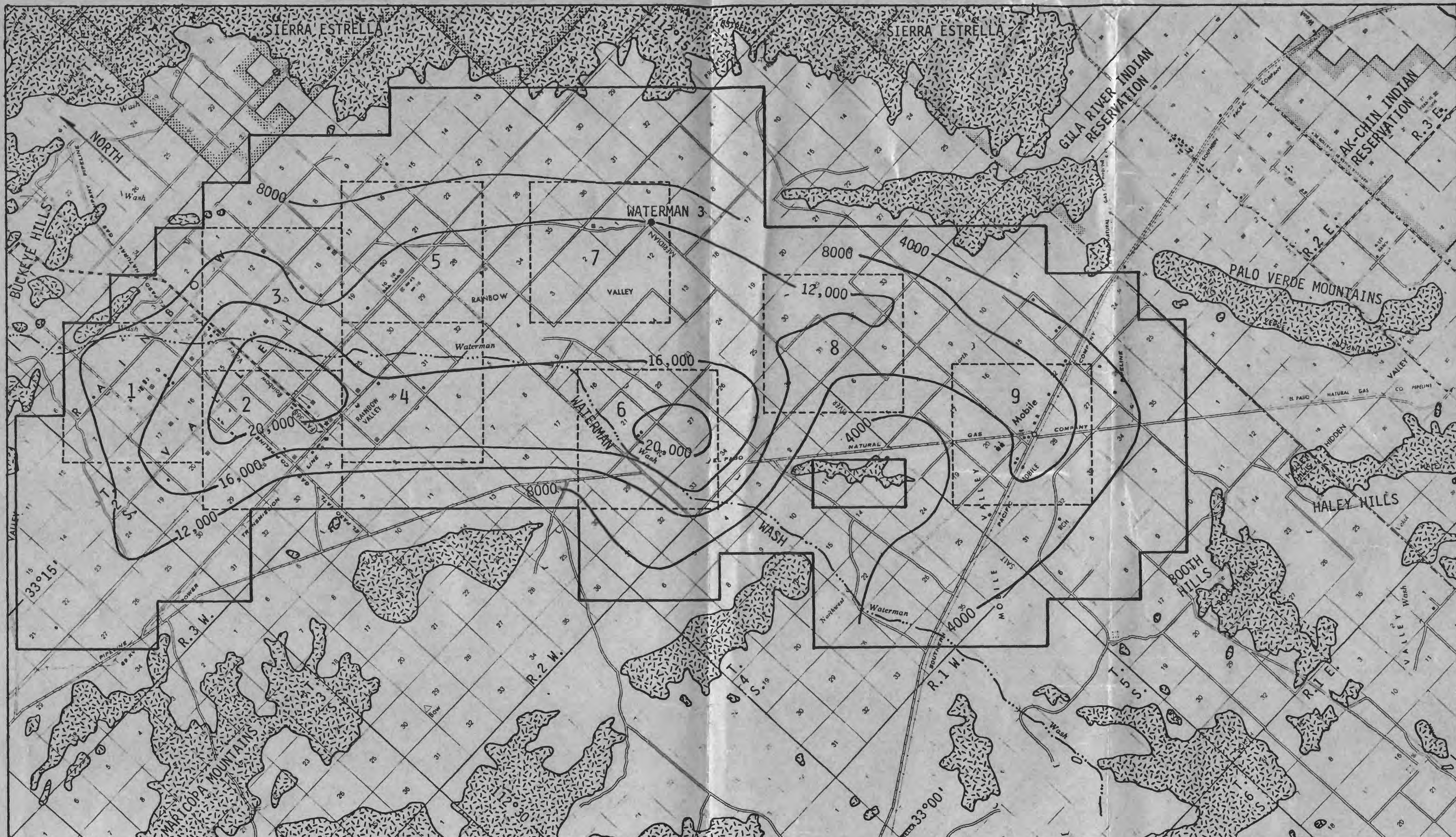
BASE FROM ARIZONA DEPARTMENT OF TRANSPORTATION 1:126,720, 1954-74

0 1 2 3 4 5 MILES

0 1 2 3 4 5 6 KILOMETERS

OUTLINE OF CONSOLIDATED ROCKS FROM WILSON (1979)

Figure 8

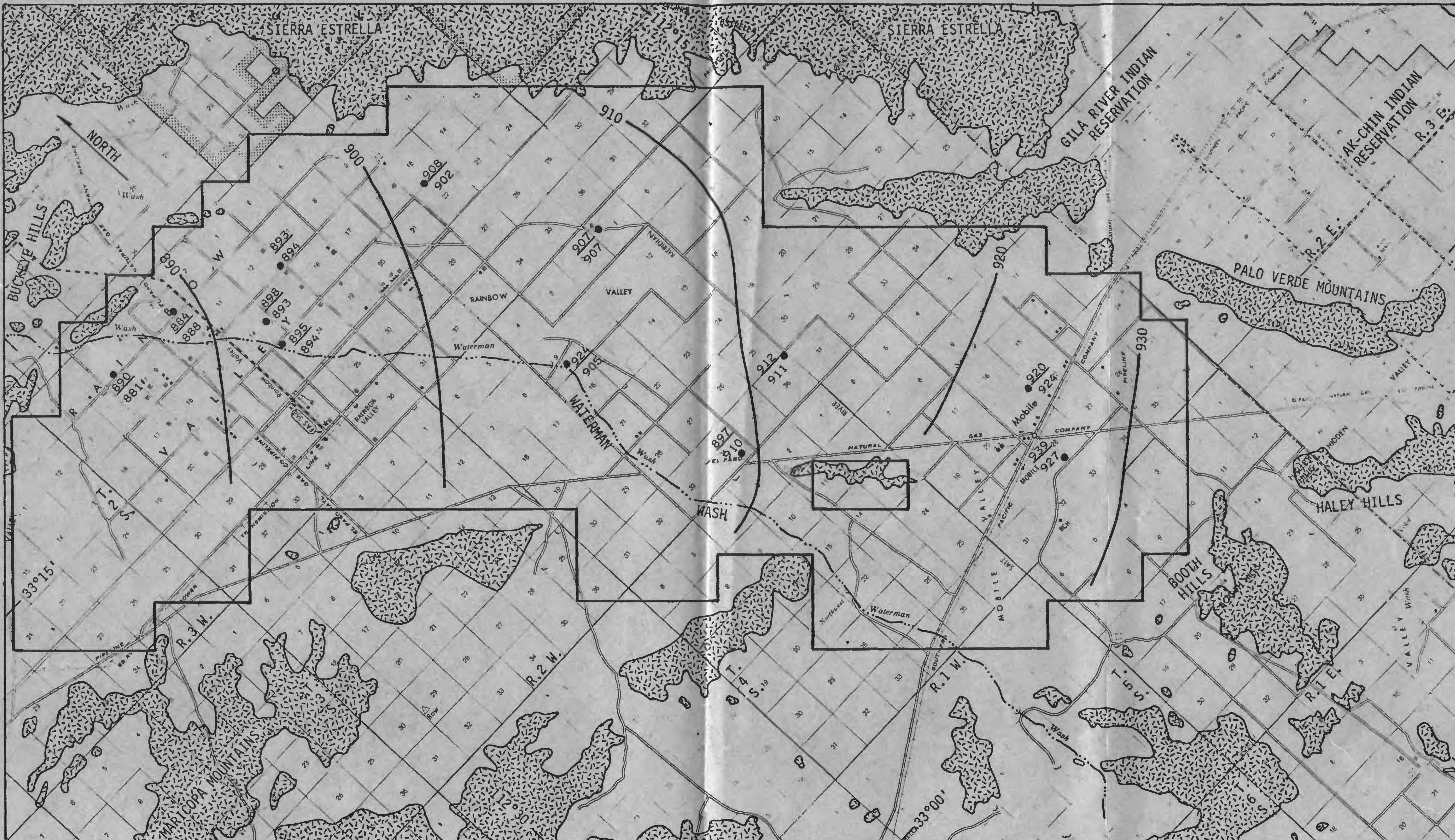


BASE FROM ARIZONA DEPARTMENT OF
TRANSPORTATION 1:126,720, 1954-74

0 1 2 3 4 5 MILES
0 1 2 3 4 5 6 KILOMETERS

OUTLINE OF CONSOLIDATED ROCKS
FROM WILSON (1979)

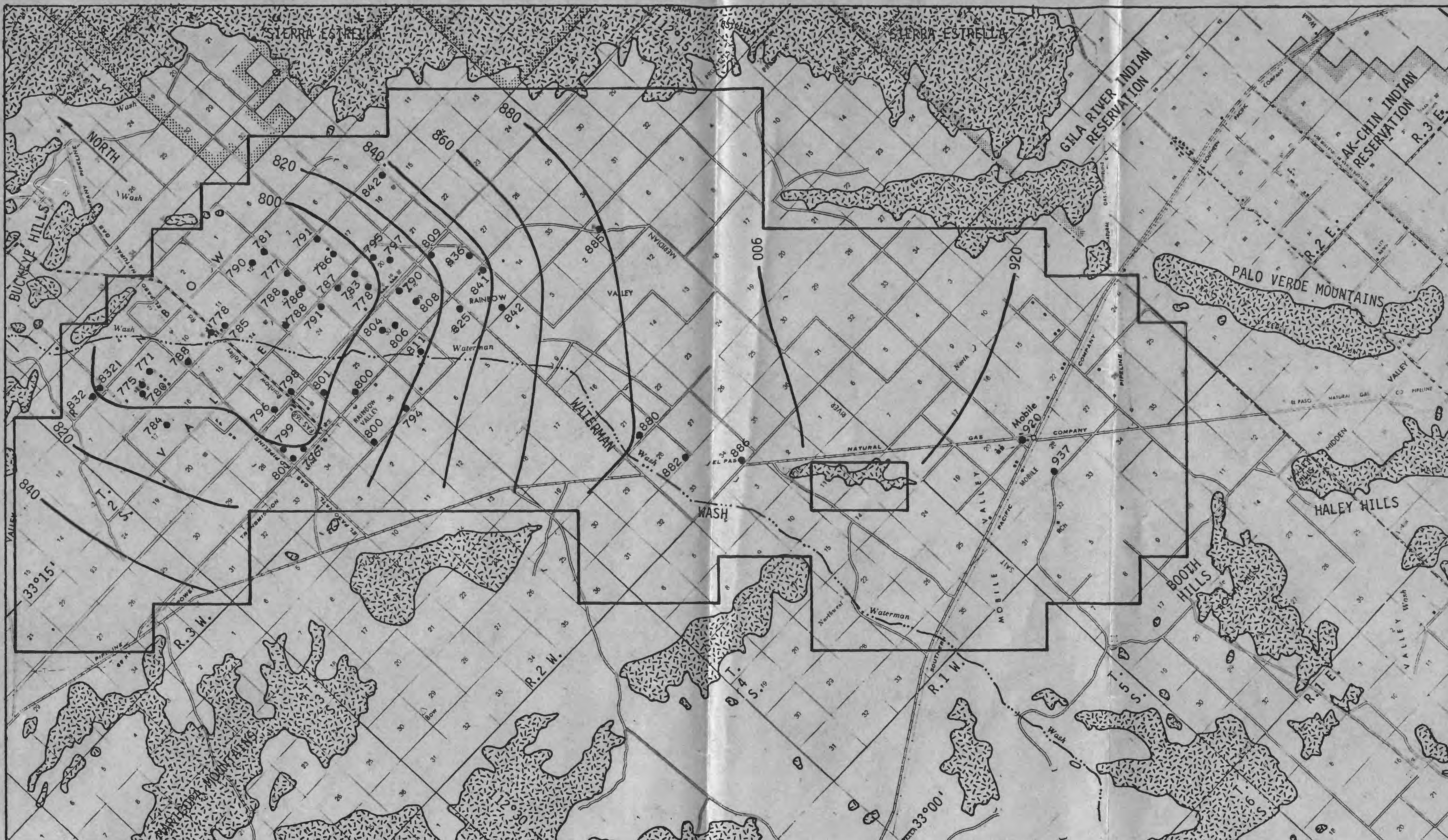
Figure 9



BASE FROM ARIZONA DEPARTMENT OF TRANSPORTATION 1:126,720, 1954-74

OUTLINE OF CONSOLIDATED ROCKS FROM WILSON (1979)

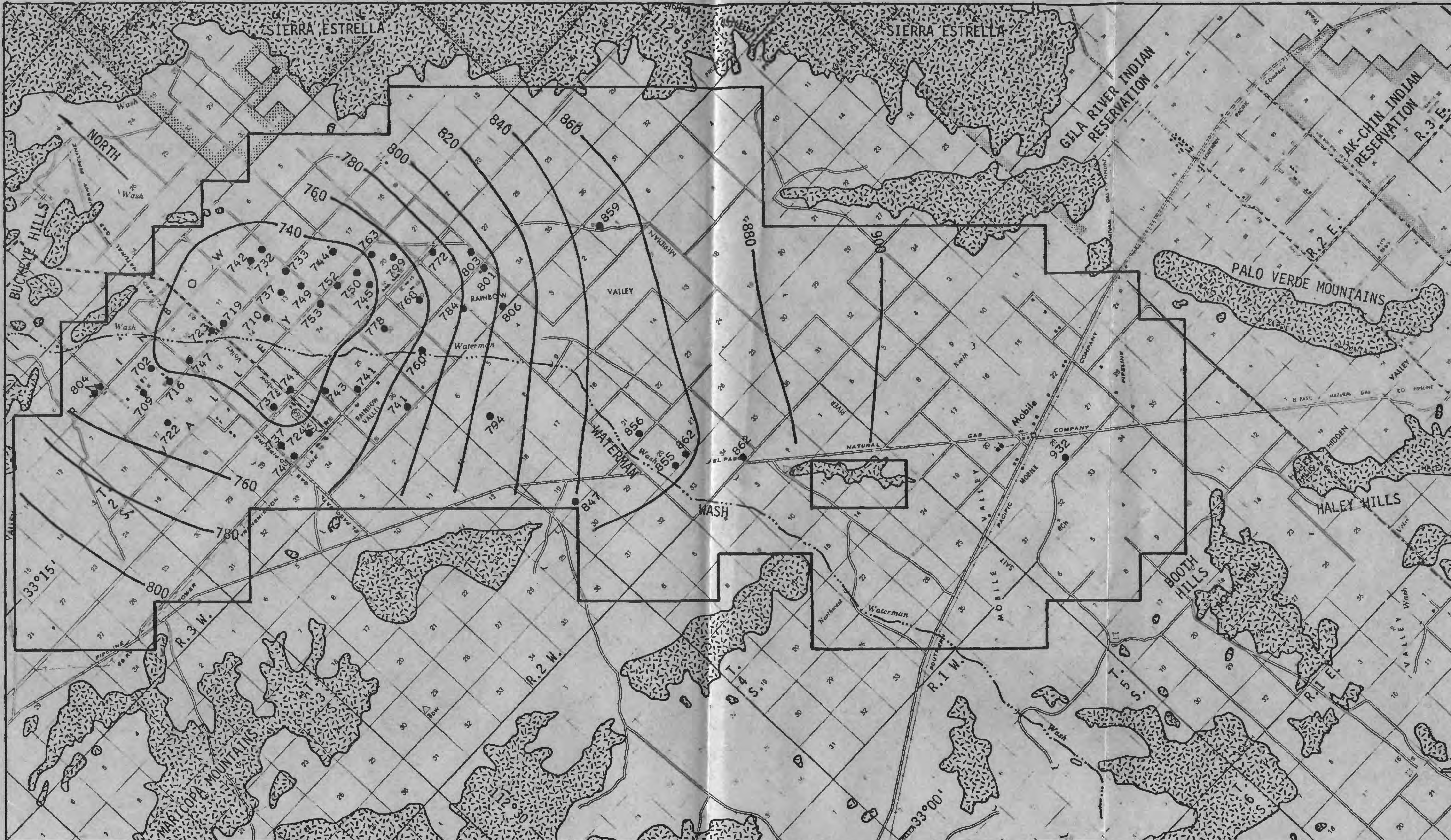
Figure 10



BASE FROM ARIZONA DEPARTMENT OF
TRANSPORTATION 1:126,720, 1954-74

OUTLINE OF CONSOLIDATED ROCKS
FROM WILSON (1979)

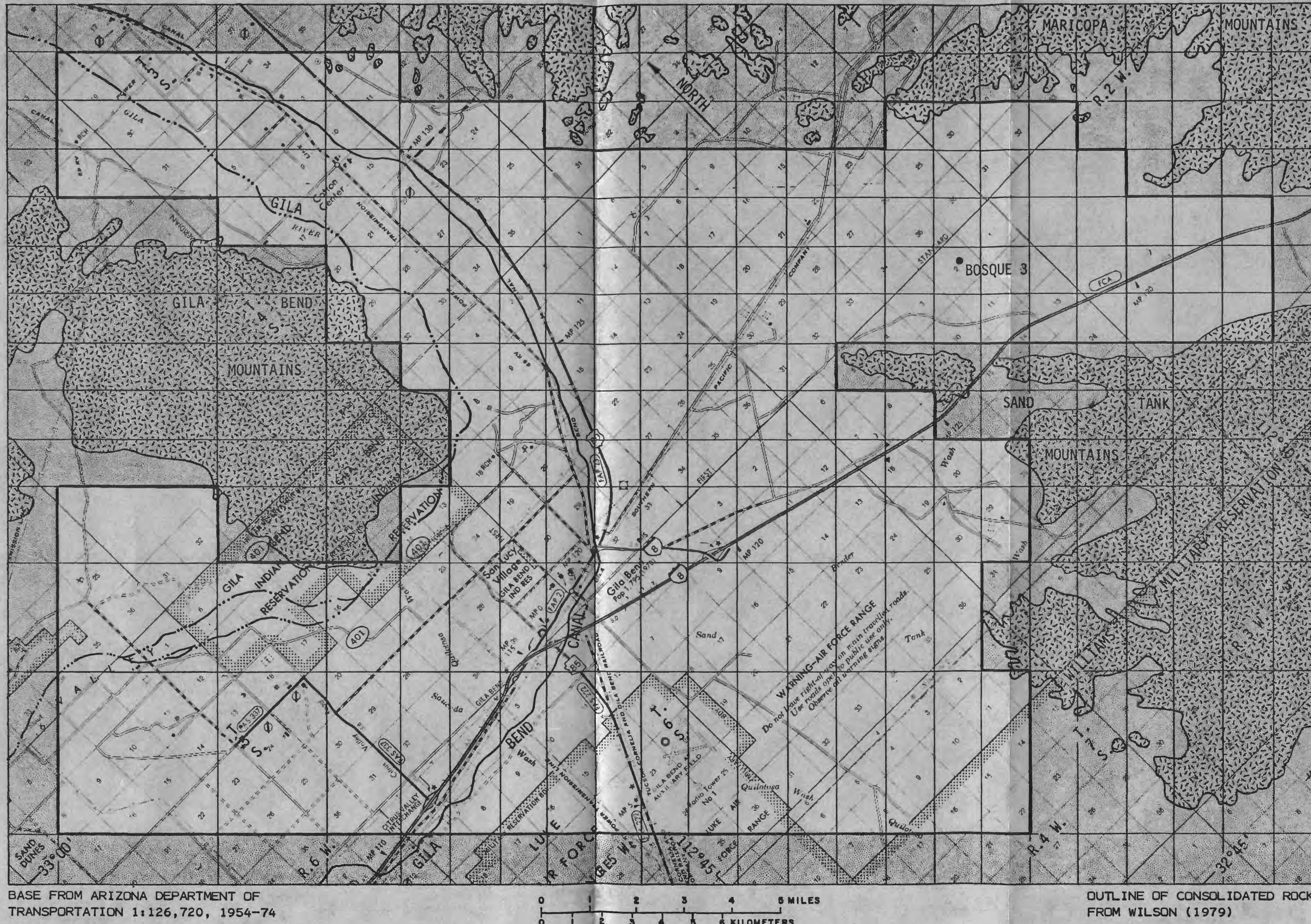
Figure 11



BASE FROM ARIZONA DEPARTMENT OF TRANSPORTATION 1:126,720, 1954-74

OUTLINE OF CONSOLIDATED ROCKS FROM WILSON (1979)

Figure 12



BASE FROM ARIZONA DEPARTMENT OF TRANSPORTATION 1:126,720, 1954-74

OUTLINE OF CONSOLIDATED ROCKS FROM WILSON (1979)

Figure 14

BASE FROM ARIZONA DEPARTMENT OF TRANSPORTATION 1:126,720, 1954-74

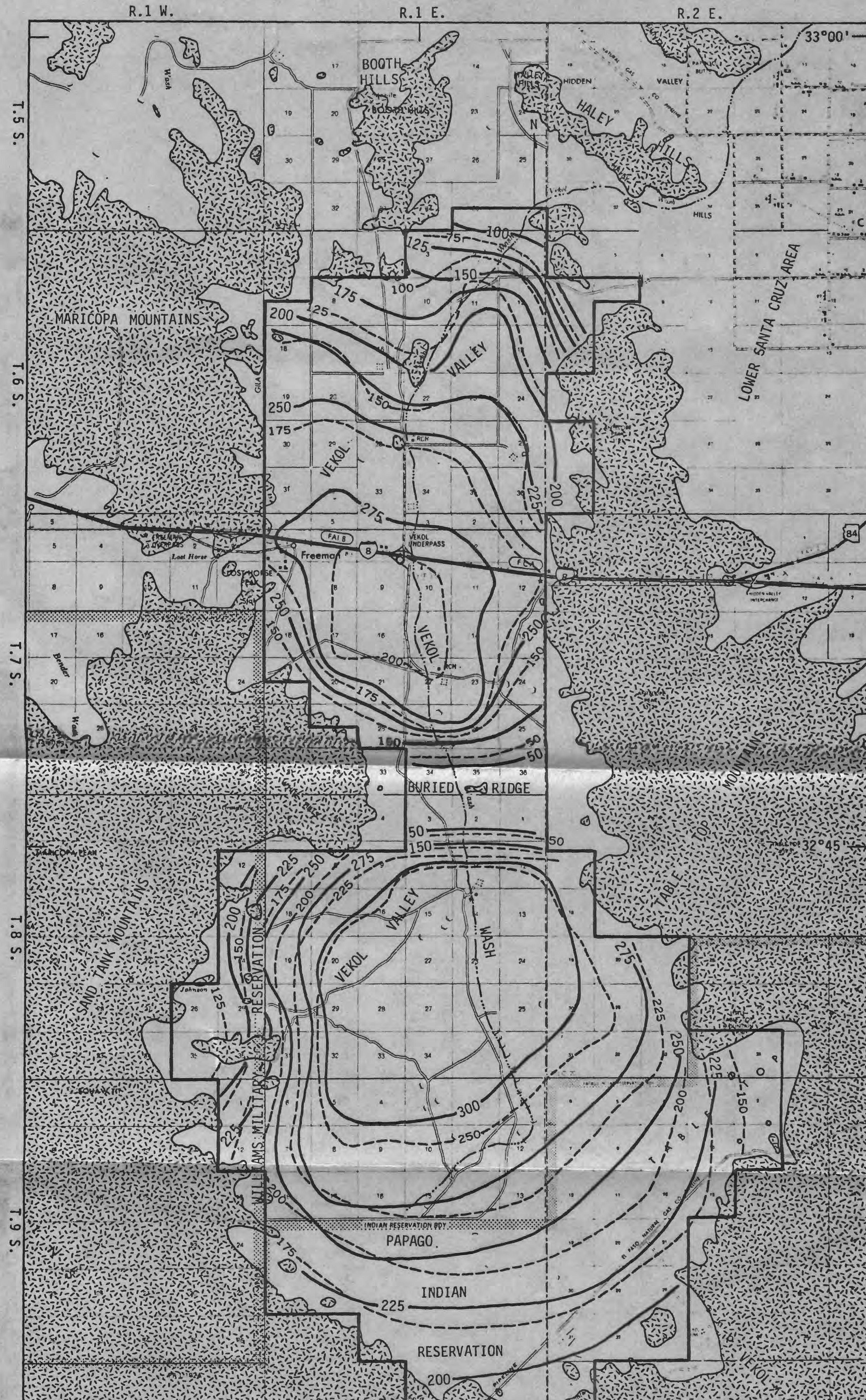
OUTLINE OF CONSOLIDATED ROCKS FROM WILSON (1979)

Figure 15

BASE FROM ARIZONA DEPARTMENT OF TRANSPORTATION 1:126,720, 1954-74

OUTLINE OF CONSOLIDATED ROCKS FROM WILSON (1979)

Figure 16



BASE FROM ARIZONA DEPARTMENT OF TRANSPORTATION 1:126,720, 1954-74

OUTLINE OF CONSOLIDATED ROCKS FROM WILSON (1979)

0 1 2 3 4 5 MILES
0 1 2 3 4 5 6 KILOMETERS

Figure 17