GROUNDWATER MODELING STUDY OF THE UPPER SANTA CRUZ BASIN AND AVRA VALLEY IN PIMA, PINAL AND SANTA CRUZ COUNTIES, SOUTHEASTERN ARIZONA

VOLUME I

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AUGUST 1984

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INTRODUCTION

The Upper Santa Cruz basin and Avra Valley (USC/AVR) in southeastern Arizona are located in one of the most heavily populated regions of Arizona. Tucson, the largest city in the area, is dependent solely on groundwater resources for a water supply. Over the past 50 years Tucson and the surrounding area has undergone dramatic growth which has severely stressed the water resources to a point where management of the resource is needed.

Due to expressed concerns of local water users, as well as various State agencies, a study was proposed by the Department of Water Resources (DWR) which would assimilate available groundwater data into a single comprehensive data base, thus among other things, avoiding duplication of data collection and study efforts by the various entities. The data base would be used to generate input for a digital groundwater model.

In the spring of 1980, the Arizona Water Commission, now the Arizona Department of Water Resources, began the digital groundwater model study of the Upper Santa Cruz basin and Avra Valley. The study was conducted by the staff of the Hydrology Division of the Department of Water Resources using funding provided by the State. The study was restricted to the collection of historical (1960-1979) data and no new field investigations were undertaken for this study.

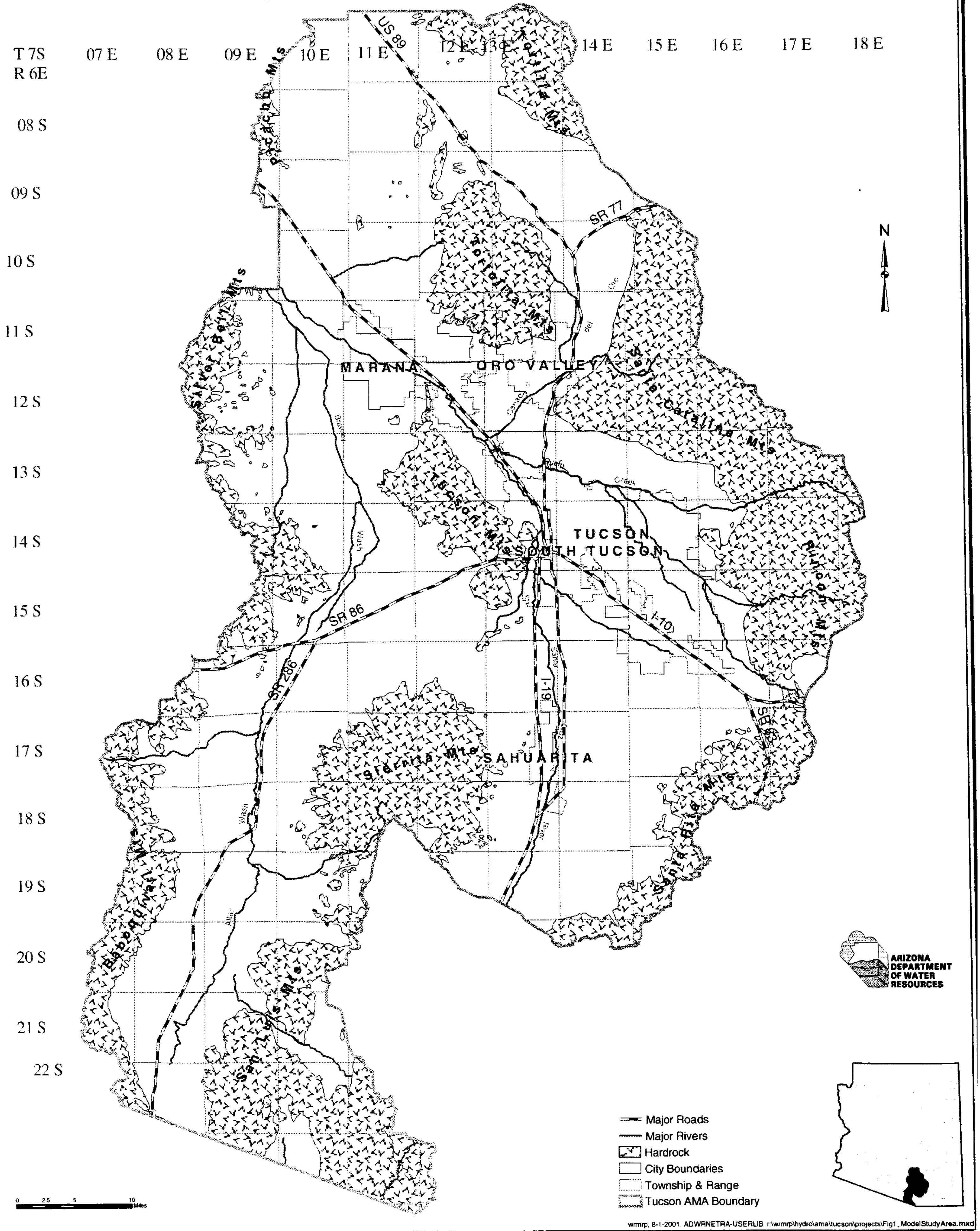
The cooperation of the various water users and data collectors in the USC/AVR area was solicited. Numerous data requests were made of these water users and the data provided form the foundation of the data base. The data base was synthesized into the necessary computer format needed for operation of the digital model. The results of the study are a large comprehensive data base and a calibrated and verified digital groundwater model.

Purpose and Scope of Investigation

The purpose of the study included two objectives. First, to establish a complete computerized groundwater data base for the study area (see fig. 1). Second, to develop a digital groundwater model that can be utilized by the DWR and local agencies in their groundwater planning and management programs and as a guide for future data collection efforts.

A two-dimensional digital finite-difference groundwater model was selected as the method of investigating the groundwater system. The use of a two-dimensional model was adopted based on the fact that the groundwater flow system generally reacts as a two-dimensional system.

Figure 1. Model Study Area



GEOGRAPHIC SETTING

The USC/AVR area is in the Basin and Range physiographic province (Fenneman, 1931), which is typified by broad, gently sloping alluvial basins separated by north to northwest trending fault block mountains.

Upper Santa Cruz Basin

The Upper Santa Cruz basin is an intermontane basin, the surface of which is a gently sloping (average slope 20 feet per mile) alluvial plain that trends south to north. The area of study within this basin is bounded on the east by the Rincon, Empire and Santa Rita Mountains; on the west by the Tucson Mountains, Black Mountain, and the Sierrita Mountains; and on the north by the Tortolita and Santa Catalina Mountains. The major surface drainage is the Santa Cruz River and its tributaries: Canada del Oro Wash, Rillito Creek, and Sopori Wash (see fig. 1).

The Santa Cruz River enters the basin at the international border east of Nogales, flows north about 85 miles, and exits the basin near Rillito. Canada del Oro Wash begins in the Santa Catalina Mountains and flows south-southwest about 30 miles to its confluence with the Santa Cruz River eight miles southeast of the town of Rillito. Rillito Creek, joined by Sabino Creek, Tanque Verde Creek and Pantano Wash, begins in the Rincon Mountains and flows west-northwest 12 miles to its confluence with the Santa Cruz River about seven miles northwest of Tucson. Sopori Wash begins in the western part of the basin and flows northeast to its confluence with the Santa Cruz River near the town of Amado.

The Santa Cruz River and its tributaries are intermittent streams. Flow in the Santa Cruz is extremely variable and many of the tributaries are subject to flash flooding.

The Upper Santa Cruz basin is one of the most heavily populated areas in Arizona. The major population center is the city of Tucson. Smaller towns within the area of study of the basin include Cortaro, Rillito, Oro Valley, South Tucson, Vail, Sahuarita, Continental and Green Valley.

The economy of the Upper Santa Cruz basin is supported by many industries. Copper mining and its support industries provide a large economic base while manufacturing and governmental operations play a significant role in the basin's employment. Agriculture is another large economic factor with cotton and pecans being the major crops. All of these industries rely entirely on the groundwater resources of the area. Other large groundwater users include sand and gravel operations and power production.

Avra Valley

Avra Valley, similar to the Upper Santa Cruz basin, is an alluvial basin with a gently sloping plain (average surface slope 18 feet per mile) that trends south to north. The plain is bounded on the east, and separated from the Upper Santa Cruz basin by the Tortolita and Tucson Mountains, Black Mountain, and the Sierrita Mountains; on the west by the Silver Bell and

Roskruge Mountains. The northern boundary is roughly the Santa Cruz River channel. The southern boundary of the study area has been chosen at the township line between T16S and T17S.

The major surface drainage is Brawley Wash. Brawley Wash enters the valley six miles south of Three Points and continues to flow north-northeast approximately 25 miles to a point five miles west of Marana where it is renamed Los Robles Wash and parallels the Santa Cruz River. Los Robles Wash then exits the area north of the Silver Bell Mountains about seven miles southwest of Red Rock. The Santa Cruz River flows across the northern end of the area. It enters the valley north of the Tucson Mountains about five miles southeast of Marana and flows about 12 miles west-northwest and exits the area of study north of the Silver Bell Mountains about eight miles west of Red Rock. Los Robles Wash joins the Santa Cruz River west of the area (see fig. 1).

Avra Valley is sparsely populated. Small towns in the valley are Marana, Three Points and Silverbell. Large and small farms along with small subdivisions account for a majority of the population within the basin.

Agriculture is the main industry of Avra Valley and the largest water user. The primary crops are cotton, alfalfa and assorted grains. Other crops include corn, lettuce, sorghum, orchard crops, pecans, beets and pasture lands. Copper is also mined in the Silver Bell Mountains.

HYDROGEOLOGY

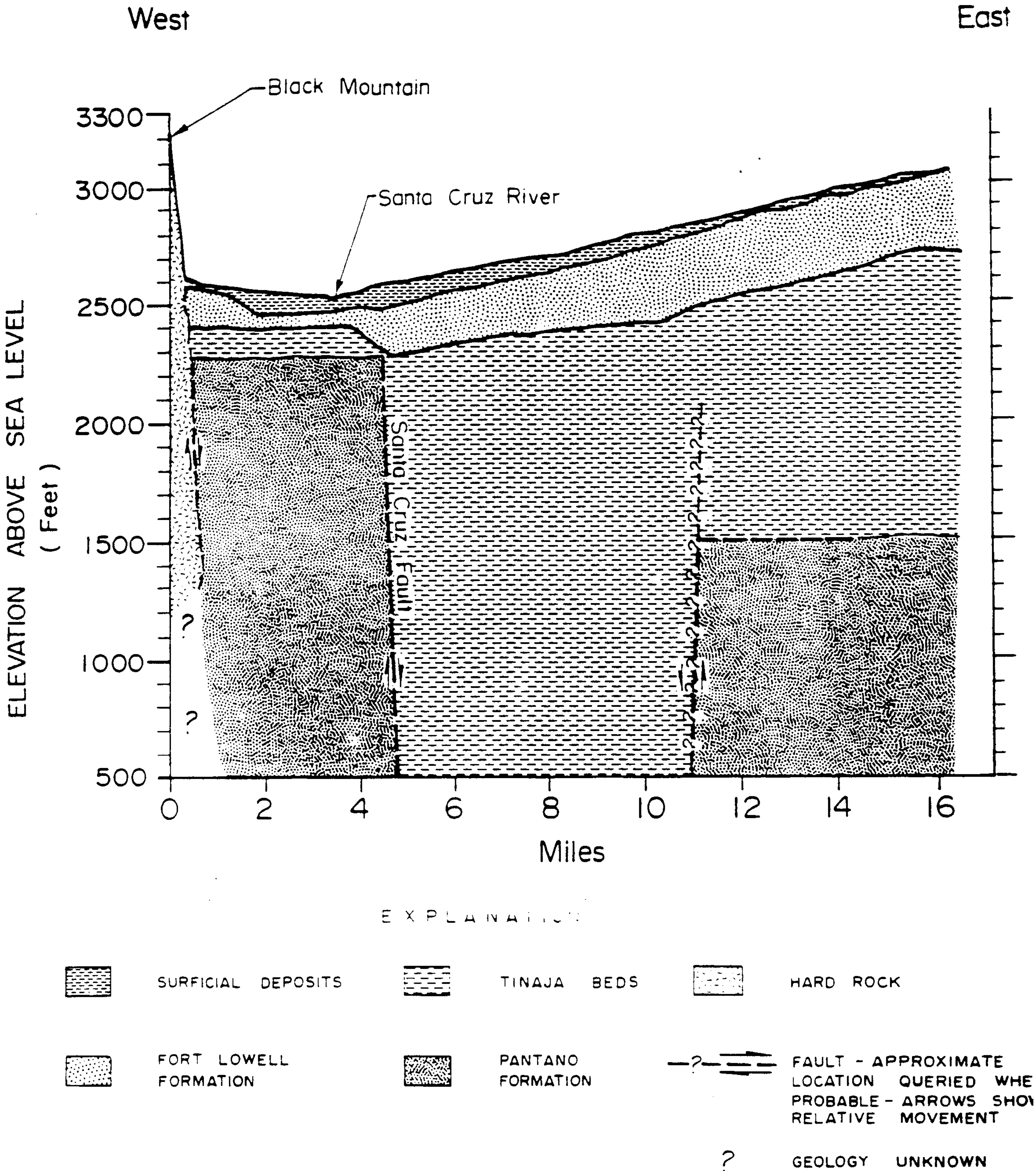
The source of water in the Upper Santa Cruz basin and Avra Valley is groundwater that occurs in the basin-fill sediments. Small amounts of groundwater do occur locally in thin alluvium in stream channels that drain the mountains surrounding the area, and in fractured and weathered volcanic, granitic, metamorphic and sedimentary rocks that comprise the mountains.

Upper Santa Cruz Basin

As a result of work done by Davidson (1973), three major units forming a single aquifer have been delineated in the USC basin-fill sediments. The units, in ascending order, are: the Pantano Formation, the Tinaja Beds, and the Fort Lowell Formation (see fig. 2).

The Pantano Formation is generally a reddish-brown silty sandstone to gravel. The formation is more tightly cemented in surface exposures, which occur in the foothills of the Santa Catalina, Rincon, and Sierrita Mountains, than in fresh core samples from wells (Davidson, 1973). Near Davidson Canyon, the Pantano Formation is at least 6,400 feet thick (Finnell, 1970). In the central part of the Tucson area and northern part of the Sahuarita-Continental area, over 1,000 feet of Pantano have been penetrated by wells. Large-diameter wells completed in the Pantano Formation yield from a few hundred to as much as 5,000 gallons per minute (gpm).

The Tinaja beds are composed of upper beds of gray to grayish-brown sandy gravels and of lower beds, which range from a



GENERALIZED GEOLOGIC CROSS-SECTION

Upper Santa Cruz Basin (after Davidson, 1973)

Figure 2

gray to grayish-brown sandy gravel to a reddish to medium-brown gypsiferous clayey silt and mudstone from west to east across the Santa Cruz fault. The Tinaja beds range in thickness from up to several hundred feet near the edges of the basin to more than 2,000 feet thick in the center of the basin (Davidson, 1973). These beds crop out in the same mountain foothills as the Pantano Formation. Yields of greater than 600 gpm have been reported for wells tapping permeable coarse-grained beds.

The Fort Lowell Formation consists of unconsolidated to moderately-consolidated sediments ranging in color from dark to light reddish brown. The formation grades from a silty gravel near the edges of the basin to a sandy silt and clayey silt that is 300 to 400 feet thick in the central part of the basin. Surface exposures occur in the foothills of the Sierrita Mountains and along streams, roadcuts, mine pits and steep hills. The Fort Lowell Formation covers the Tinaja beds, which may overlay either the Pantano Formation or bedrock. Well yields of 500-1500 gpm from the Fort Lowell Formation are common (Davidson, 1973).

The water-bearing properties of the basin fill alluvium have been categorized (Laney, 1972). The Pantano Formation has a measured upper permeability value of 100 gpd/ft^2 and a range in porosity values of 20-27 percent. The Tinaja Beds have permeability values ranging from 10 to 400 gpd/ft^2 with porosity values of 24-35 percent. The Fort Lowell Formation has a range in permeability values of 150-700 gpd/ft^2 and porosity values of 26-34 percent.

The majority of the groundwater pumped in the USC comes from the upper two units, the Fort Lowell Formation (where saturated) and the Tinaja beds. Some water is taken from the Pantano Formation but, due to its relatively low permeability and considerable depth, it is not often tapped.

Groundwater flow in the USC basin is generally northwestward. This flow is a product of northerly flow from the southern portion of the basin and westerly flow from the eastern portion of the basin, creating a northwesterly flow as it exits the basin at the Rillito Narrows.

Depths to water in the USC basin measured during 1960-1980 range from less than 10 feet along some stream channels to greater than 550 feet in some areas. Changes in water-levels over this same time period have ranged from a rise of 30 feet to declines of up to 120 feet, with an areally weighted average of approximately 50 feet of water-level decline.

Avra Valley

In Avra Valley the main water-bearing unit is the alluvial fill along the central axis of the valley. The alluvial fill may be as much as 2,000 feet thick and is composed of interfingering lenses of silt, sand and gravel (White and others, 1966) that, when saturated, may yield more than 3,000 gallons per minute of water to properly constructed wells. Along the fringes of the valleys, pediments may exist where the alluvial fill is underlain by bedrock at shallower depths than in the central parts of the valley. The possibilities of high well yields in these areas are reduced by the small saturated thickness of alluvial fill. The bedrock (granitic, metamorphic, volcanic and crystalline sedimentary rocks) that comprises the mountains that border the valley to the east and west may yield small amounts of water to wells where sufficiently faulted or fractured. Thin alluvial deposits along narrow valleys in the mountains also may yield a few gallons per minute to stock and domestic wells.

Groundwater movement in Avra Valley is generally from south to north paralleling Brawley Wash. The slope of the water surface is primarily northeastward and then northward, conforming, in general, to the slope of the land surface.

During the 1960-1980 period, depths to water in Avra Valley have ranged from a minimum of 50 feet to as much as 785 feet below land surface. Changes in water levels have ranged from about zero to more than 100 feet of decline over the 20 year period. The average change in water levels for this area and time period is -60 feet.

MODELING EFFORT

The method of investigation in the USC/AVR study involved the use of a two dimensional (2-D) digital finite-difference groundwater model. The computer model program used in the USC/AVR study is a modified version of the U.S. Geological Survey three dimensional (3-D) finite-difference groundwater flow model (Trescott, 1975). This model is capable of simulating groundwater flow both horizontally and vertically. The model program has the capability, through input options, of being used for horizontal flow only (a 2-D model), which is the configuration adopted for the USC/AVR study. The reason for choosing the 2-D configuration is that available data suggest that the aquifer system responds to stress over a long period of time as a single unit in the upper 500 to 700 feet where it has been penetrated by the majority of wells (Davidson, 1973).

Modifications were made to the model program to enhance data input and output procedures. These modifications make the model more efficient for the type of computer system available to the DWR but do not alter the solution technique.

Data Sources

Executive and technical committees, comprised of the representatives of the major water users and agencies interested in water data collection in the area, were formed to assist in acquiring existing and additional hydrologic data and provide input for the study. These committees were composed of representatives from Tucson Water, the University of Arizona, Pima Association of Governments, U.S. Geological Survey, Farmers Investment Company, Cortaro Water Users Association, Duval Corporation, Anamax Mining Company, ASARCO Incorporated, Cyprus-Pima Mining Company and Avra Valley Land Owners Association.

Data needs for the model include water-level elevations, pumpage and recharge quantities, and aquifer transmissivity and specific yield. To supply the data, all sources within the Arizona Department of Water Resources were reviewed. The DWR Certificate of Exemption files were reviewed for reported pumpage for those groundwater users that had received a Certificate of Exemption to pump a specified quantity of groundwater from the existing designated critical groundwater areas (before the 1980 Groundwater Management Act). Other internal sources of data consisted of previous studies of the area, including the Army Corps of Engineer's **Tucson Urban Study Model**, and files on the Central Arizona Project, Water Rights and Subdivisions.

Additional data were supplied by local water users and data collectors including mining companies and agricultural entities. Especially helpful were the data supplied by Tucson Water, the University of Arizona's Soils, Water and Engineering Department, and the U.S. Geological Survey Water Resources Division (WRD). Other sources of data included records from Pima County Superior Court, private water companies, the state library, the Corporation Commission, and both the Ina and Roger Road Sewage Treatment Plant reports.

Modeled Area

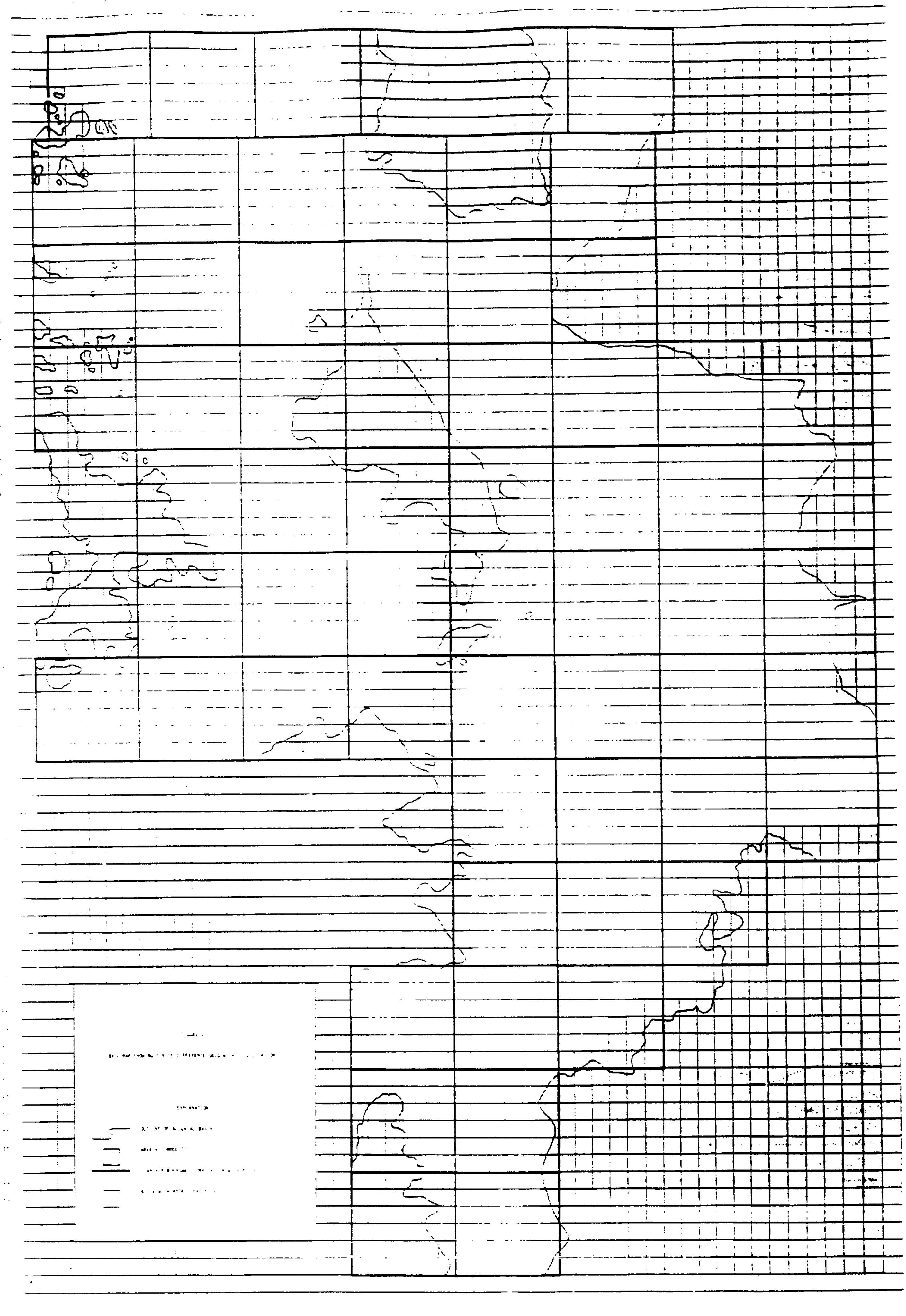
The modeled area encompasses all of Avra Valley and the northern portion of the Upper Santa Cruz basin, along with a very small portion of the Lower Santa Cruz basin. Mountain ranges surround the modeled area on all sides. The area is 72 miles long and 48 miles wide, actively modeling 1619 square miles. The modeled area is defined by the Roskruge Mountains on the west, the Catalina, Rincon and Santa Rita Mountains on the east, the southern boundary of Township 16S in Avra Valley, the southern boundary of Township 21S in the USC basin, and the northern boundary of Township 10S on the north. These boundaries were selected based on available hydrologic data, and in general, conformance with previous USGS water resources investigations (Anderson, 1972, Moosburner, 1972, and Davidson, 1973). Altar Valley, south of Avra Valley, as well as the southern portion of the USC basin, were not included in the actively modeled area due to the lack of available hydrologic data.

Model Development

In developing a model for the USC/AVR area, the area to be modeled was divided into a uniform grid with each square representing one square mile. Common practice is to describe the rectangular, finite-difference elements as blocks. The center of the block is the node which is the point in space for which the finite-difference equation is solved. Most of the blocks coincide within a quarter of a mile with township/range lines and closely overlay sections. Due to some township/range line offsets, a computer program was written to translate the legal description (township, range, section, and quarter section) into a block location. The blocks form a grid 50 columns wide by 74 rows long (see fig. 3). Each node is classified as either inactive or active. Active nodes represent areas within the modeled groundwater basin. Inactive nodes represent areas that are not part of the groundwater system or areas that were not modeled. There are currently 1619 active nodes in the model. The model's computer program solves the differential equations for groundwater flow between nodes, balancing inflows, outflows, and changes in storage.

Calibration Process

Calibration of the model during the 1960 to 1970 period involved first entering the known data into the model and running the model to see if it will adequately simulate the known system. This initial run was, as expected, not satisfactory and so began the task of reasonably adjusting the values of the model input data so that differences in calculated water-level elevations versus measured water-level elevations for the simulated period were minimized. The order in which the different types of data were adjusted was based on initial assumptions as to their reliability. Modifications were limited to reasonable ranges for the value of each parameter. The order of reliability, from the most to the least reliable, was as follows:



1. Water-Level Elevations

2. Pumpage

3. Aquifers Areal Extent

4. Transmissivity

5. Recharge Distribution

6. Specific Yield

In addition to decisions on modifications of the model input data involved in calibration, a decision had to be made as to when the model was sufficiently calibrated. Hydrologic models cannot be calibrated to perfect accuracy because a model is never as complex as the system simulated. It is always necessary to simplify the conceptualization of a complex aquifer system by dividing it into less complex components which can be defined by approximations. In the case of a digital model these approximations are mathematical. Models are judged to be a valid simulation of the real system (sufficiently calibrated) when the simulated results appproximate the measured results within the limits defined as the acceptable difference criteria. Acceptable difference, which is different for each model, is generally subjective, is based on sound hydrologic judgement, and is dependent on the adequacy of the generalized input data to simulate a complex hydrologic and geologic system. The difference associated with each of the data input types indicate the degree of calibration that may be achieved. For example, if the model's water-level elevations, which represent the average over the one square mile blocks, are accurate to within plus or minus 20 feet, as most are in the USC/AVR area, the model should not be expected to calibrate any closer.

The acceptable difference criteria is generally controlled by the adequacy of the input data. However, the number of calibration attempts to reach the difference criteria is controlled by the sensitivity of the model to changes in input data, as well as the type, magnitude and extent of these changes. Shortcomings inherent in any modeling effort, such as inadequate data or wrong concepts or assumptions concerning poorly understood aspects of the aquifer system, may make it impractical to reach the desired difference criteria. In this case, calibration attempts are terminated when reasonable changes in the input parameters cease to make significant improvement in the model results when compared to actual data.

In the USC/AVR study, the average absolute difference was one of the main criteria used to evaluate model adequacy for calibration. Average absolute difference is defined as the difference between the model calculated water levels and the measured water levels at the end of the simulation period. This indicator is only a guide and must be evaluated with full consideration of the distribution of difference in the system. Understanding the areas where large differences occur and the reason for the differences is important to the interpretation of the model results.

A value of ±20 feet was chosen as an acceptable average absolute difference because it represents the possible error in averaging water-level elevation for each block. It is unreasonable to expect the model to calibrate closer than the possible differences in the primary input data.

Changes in the input data during the calibration process were made only within reasonable values, reasonable values being the estimated range of minimum to maximum for each parameter within the documented ranges of values in published literature. Within these criteria, a majority of the model did adequately duplicate the natural system.

Verification Process

The next step was the initiation of verification runs. The verification runs were designed to independently test the parameters and assumptions used in the final calibrated model. The time period (1970-1979) was run using the values from the ending calibration run of the input data for natural recharge, transmissivity, specific yield and boundary conditions and adding the new values for pumpage, agricultural, municipal and industrial recharge, and measured beginning (1970) and ending water levels (1980). Only minor adjustments to these parameters were allowed to prevent severely altering the results of the calibration process.

If after these runs are made, no significant increase in difference occurs, it can be said that the input parameters are justified and the system has been reasonably modeled and simulated.

MODEL INPUT PARAMETERS

Model input parameters consist of nodal values for beginning and ending water-level elevations, specific yield, transmissivity, pumpage, recharge and boundary conditions. Every effort was made to gather direct measurements or observations for each of these input parameters, and when not available, reasonable estimates were made based on the local hydrogeological conditions.

Water-Level Elevations

Water-level elevation data are necessary for the beginning and ending of each simulation period for each active node in the model. Water-level elevations for the end of each chosen time period must be available for comparison to the ending water-level elevations calculated by the model.

Three water-level maps were needed to supply beginning and ending water-level elevation data for the two simulation periods: 1960-1969 and 1970-1979. Water-level elevation maps for 1960 and 1970 were used for the first period and 1970 and 1980 water-level elevation maps for the subsequent period.

The University of Arizona's Soils, Water and Engineering (SW&E) Department supplied water-level elevation contour maps for 1960 and 1970 along with the supportive data. Some minor recontouring of water levels was necessary due to improved information on the geology for some areas. For the 1980 water-level map, data from the DWR Basic Data Unit, Tucson Water, U.S.

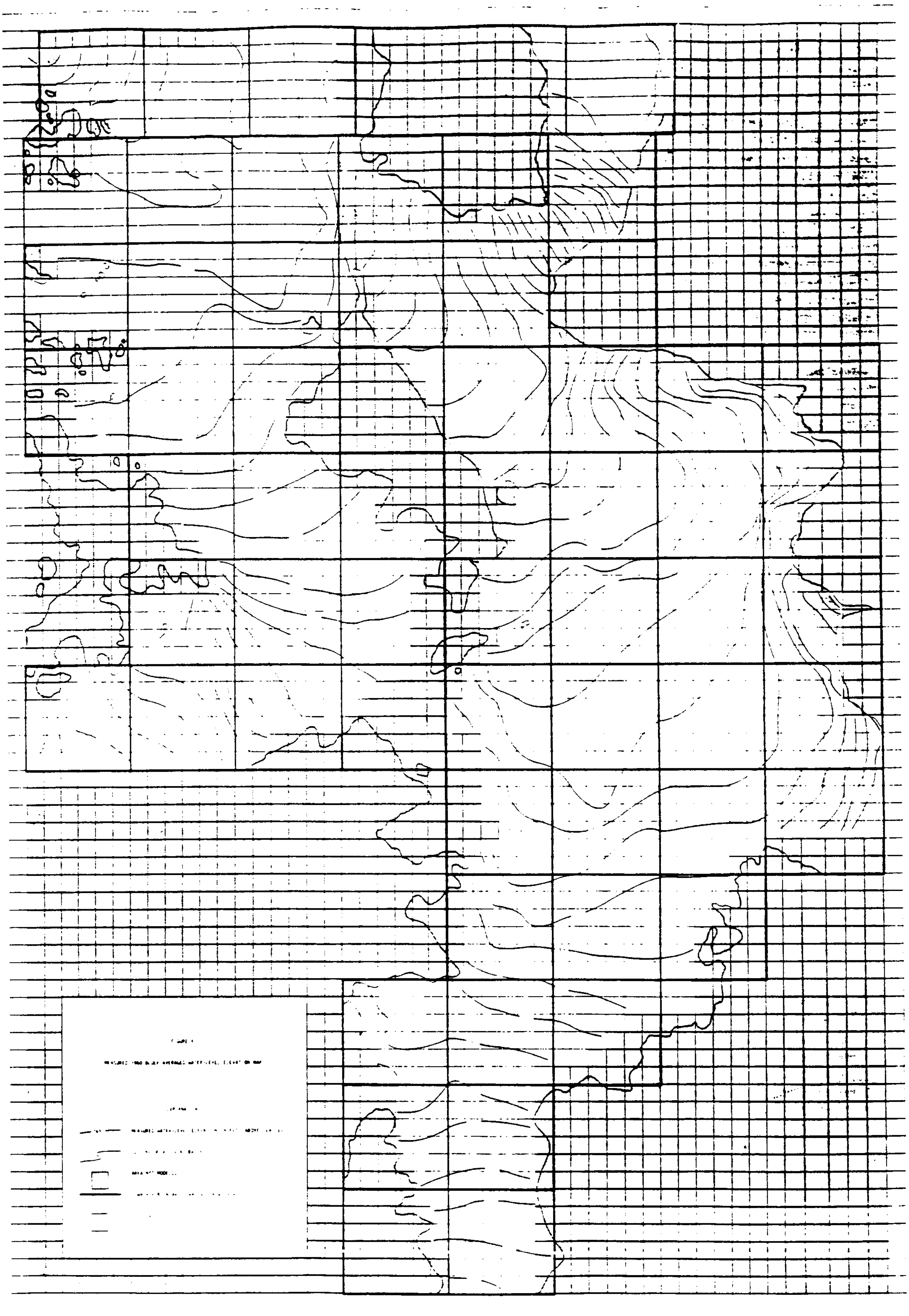
Geological Survey and University of Arizona's SW&E Department were plotted and contoured.

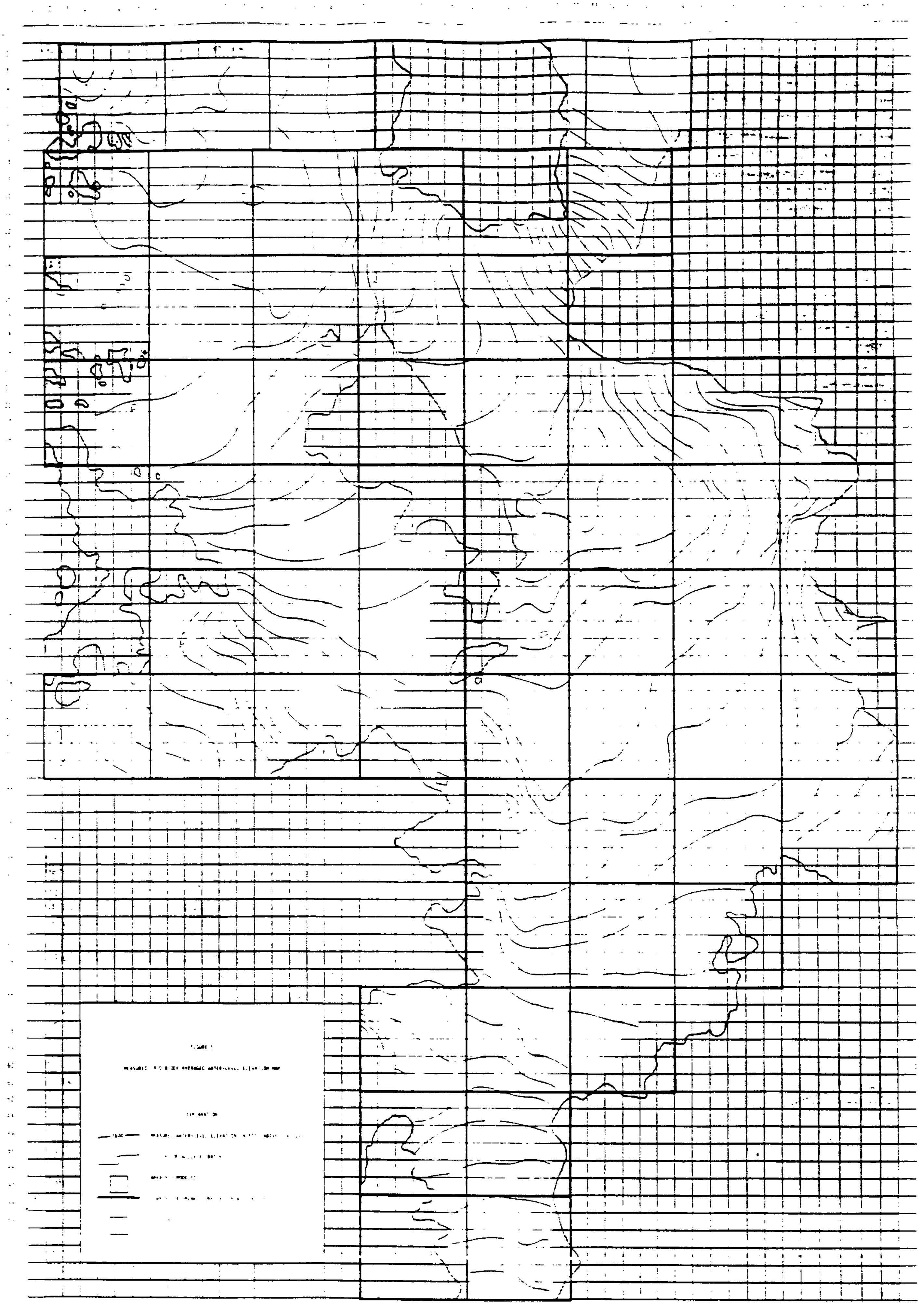
An average water-level elevation was determined for each model block for each of the water-level elevation maps (see figs. 4, 5 & 6). These data were entered into the model file where they would act as the beginning and ending water-level elevations for the model (see table 4).

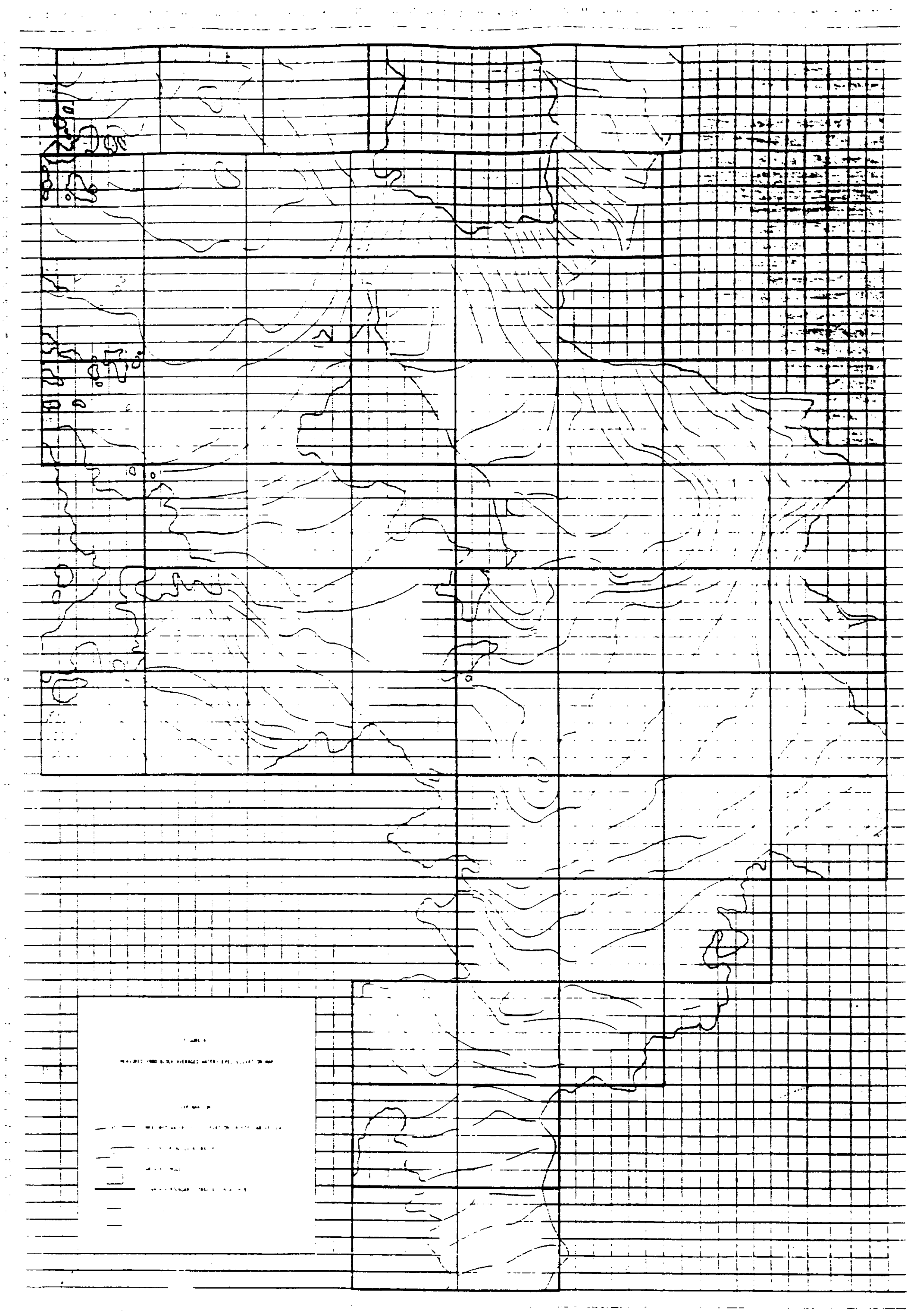
Specific Yield

Specific yield is a measure of an aquifer's ability to yield water from storage to wells. Specific yield is defined as the ratio of 1) the volume of water in a saturated unit volume that will drain by gravity to 2) the unit volume (Meinzer, 1923). Values of specific yield can be derived from 1) aquifer tests, 2) volumetric changes in storage analyses, and 3) laboratory determinations of specific yield based on similar aquifer materials.

Due to a lack of measured data, the USC/AVR study used a computerized version of method number three, developed by the Department of Water Resources, called the DWR Drillers' Log Program (Long and Erb, 1980). The program calculates both specific yield and transmissivity. The program utilizes the drillers' description of the aquifer material encountered and assigns to each an empirically determined specific yield value based on laboratory tests of porosity and permeability (Davis et al., 1959). A weighted average specific yield value for each drillers' log was calculated from individual specific yield values assigned to each material type listed on the log. As an







example see Figure 7. The specific yield values for each well were then plotted and zones of very low (.01 - .05), low (.06 - .10), moderate (.11 - .15), high (.16 - .20) and very high (.21 - .25) specific yield were delineated. Specific yields for areas with no drillers' logs were estimated on the basis of surrounding values. A grid map was overlaid on the specific yield zone map and average values were then assigned for each active node. Over 500 drillers' logs were collected and coded from the files of the U.S. Geological Survey WRD, DWR, Tucson Water, along with those supplied by various private water companies and agricultural interests. Calculated specific yield values range from a low of .02 to a high of .25 (See table 1)

Transmissivity

Transmissivity is the measure of the ability of the entire saturated thickness of an aquifer to transmit water. Transmissivity is defined as the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman, 1972).

Three sources of transmissivity data were available for the study. Values were obtained from: 1) U.S.G.S. Water Supply Paper 1939-C, "Electrical Analog Analysis of the Hydrologic System, Tucson Basin, Southeastern Arizona" by T. W. Anderson; 2) U.S.G.S. Atlas HA-25, "Analysis of the Ground-Water System by Electrical Analog Model, Avra Valley, Pima and Pinal Counties, Arizona" by Otto Moosburner; and 3) transmissivity maps from the City of Tucson, "Pattern of Regional Transmissivity 1970-1978,

FIGURE 7

Example of Estimating Specific Yield and Transmissivity Using Drillers' Logs

<u>Drillers' Log</u>		<u>Coded Log</u>		
Depth	Description	Code	Sy	K
0-20	Topsoil	SOIL	5	20
20-77	Sand	WASA	25	1500
77-135	Sand, Clay and Gravel	SCGR	10	100
135-250	Sand and Gravel	SAGR	25	1500
250-425	Clay and Fine Sand	HSCL	5	20
425-670	Sand and Gravel	SAGR	25	1500
670-900	Gravelly Clay	GRCL	5	20

*Depth to water 50 feet
Total saturated interval 850 feet

<u>Calculating Specific Yield (Sy)</u>:

$$Sy = \frac{(27'x25)+(58'x10)+(115'x25)+(175'x5)+(245'x25)+(230'x5}{850'}$$

Sy = 14.4%

<u>Calculating Transmissivity (T)</u>:

$$T = (27'x1500)+(58'x1000)+(115'x1500)+(175'x20)+(245'x1500)+(230'x20)$$

T = 594,405 gals/day/ft

(Taken from Kisser, et. al., 1981)

Tucson, Pima County, Arizona and "Pattern of Regional Transmissivity 1970-1978, Avra Valley, Pima County, Arizona. Transmissivity values in these reports were derived from aquifer tests. Additional transmissivity values were derived using the DWR drillers' log program.

Transmissivity values were selected based on their reliability, according to the following priority: 1) measured long-term aquifer tests conducted by Tucson Water and other entities, 2) average transmissivity values based on published reports, and 3) averaged transmissivity values from the DWR Drillers' Log Program. In areas where no data were available, transmissivity was estimated from surrounding node values or based on assumed aquifer thickness and permeability.

The DWR Drillers' Log Program was used to quantify initial transmissivity input values for areas with no aquifer-test data. The DWR Drillers' Log Program, using the same logs as used in estimating specific yield, assigns a permeability value to each aquifer material type in a similar manner in which specific yield is assigned. The transmissivity is calculated by multiplying the permeability of each described unit by the saturated thickness of the material. Transmissivity values obtained for each material are then summed from the water level to the total well depth to yield total transmissivity (see fig. 7). Water levels from the 1960 water-level elevation map were used as the upper water-level elevation in summing up the transmissivity values. Estimating transmissivity values this way has been used in the Salt River Valley Cooperative Study (Long et al., 1982).

From these data sources, a transmissivity zone map was produced and an average transmissivity value was assigned to each active node. Values were not adjusted as dewatering occured. Values ranged from 2,000 gpd/ft. to 290,000 gpd/ft. (see table 1). The wide range of values is common in the alluvial aquifers of the Basin and Range province where areas of coarse sands and gravels commonly have much higher transmissivity values than areas that are predominately interbedded silts and clays.

Pumpage

All major water users and private water companies in the area were requested to submit their pumpage history for each well for the period 1960-1979. In general, most water users do not measure pumpage directly; estimates are based on power consumption (electrical or gas) and/or records of the number of hours a pump operated. Other pumpage estimates were supplied by the U.S. Geological Survey WRD and the University of Arizona's Soils, Water and Engineering Department. The U.S.G.S. pumpage was based on power consumption records while the University's pumpage was based on various methods such as power consumption records, per capita consumption, user estimates, and consumptive-use data (such as 30 gallons per day per cow). The pumpage data compiled is thought to be the most comprehensive ever developed for the area, although some minor data deficiencies exist due to incomplete records.

Pumpage data were separated into three use categories: municipal, industrial and agricultural. Each node has the total of these three categories as the total pumpage for that node, but the data file listed in table 2 separates the pumpage by category.

The municipal category includes pumpage by Tucson Water, private water companies, mobile home parks and schools. The majority of municipal pumpage is by Tucson Water which supplied measured pumpage for each well. Pumpage estimates were also supplied by the University of Arizona's Soils, Water and Engineering Department and private water companies. Additional estimates were made by the DWR for wells with incomplete records, using the date the well was drilled and an average recorded or calculated pumpage.

Industrial pumpage includes power companies, mines, manufacturers, dairies, sand and gravel operations, race tracks, hospitals and airport facilities. As with municipal pumpage, data were either supplied directly by the user or estimated by various data collectors using methods such as power consumption, water use per operation, water pumped per ton of ore or water use per animal.

The agricultural category includes farms, ranches, irrigation districts, cemeteries, golf courses, country clubs and parks. Agricultural pumpage was separated into two categories: 1) estimates that were supplied directly by the water user or estimated by various data collectors, and 2) estimates based on crop surveys using consumptive-use factors.

Agricultural pumpage supplied directly by the water user include Farmers Investment Company and Cortaro/Marana Water Users Association. These data were formulated by either direct measurement or through the use of power records or hours run on the pump.

Agricultural pumpage for areas that did not measure or did not report agricultural pumpage was estimated using crop surveys conducted by the University of Arizona's Soils, Water and Engineering Department and crop consumptive-use. The annual crop survey information is available on a section-by-section, crop-by-crop basis from 1939 to 1980. Consumptive-use values were supplied by the DWR Office of Water Conservation to estimate pumpage. The annual cropped acreage by type was multiplied by the estimated consumptive-use value for that crop. The resulting value represents a net withdrawal figure for that section (block). Data were not available on water application rates and it was not possible to estimate pumpage and recharge values; thus it was decided that a consumptive-use pumpage value would be used for the node to represent the net agricultural water withdrawn. This net pumpage represents a minimum value for non-recoverable withdrawal and should be closely considered when assessing total agricultural pumpage and recharge values.

The percentage of total agricultural pumpage that was estimated using consumptive-use ranged from a low of 21% in 1977 to a high of 65% in 1960, with an average over the 1960-1979 period of 54% (see table 2A).

Pumpage is applied in the model as a total value per block per year. Table 2 represents USC/AVR pumpage in acre-feet by block by type by year. The majority of municipal pumpage is located within the city limits of Tucson. Other large municipal pumpage occurs in south central Avra Valley and along the Santa Cruz River south of the City of Tucson. Total municipal pumpage for the period 1960 through 1979 is estimated to be 1,220,926 acre-feet.

Agricultural pumpage is more widespread than other types of pumpages. The north central Avra Valley, Cortaro/Marana, and Continental areas are all heavily pumped for agriculture with a maximum pumpage of over 8,200 acre-feet in one year for a single block. Industrial pumpage is primarily mining related and is concentrated just east of the Sierrita Mountains. The remaining industrial pumpage is small and scattered throughout the Tucson area. The maximum total groundwater withdrawn for all uses in any one block for any one year was slightly over 8,200 acre-feet.

Recharge

Recharge is an important part of the area's water budget, but unlike water levels or pumpage, it cannot be measured directly and, therefore, is difficult to quantify. Recharge varies greatly over the modeled area depending on land use patterns, water sources, meteorological conditions and aquifer and geologic characteristics.

Potential recharge is greater in areas of high infiltration capacity, such as along river beds, and/or areas of high water application such as irrigated agricultural lands. Recharge has been separated into two categories and several sub-categories: (1) Natural: (a) Mountain front and (b) Stream flow; and (2) Incidental to use: (a) Agricultural irrigation, (b) Industrial and (c) Municipal (sewage effluent) (see table 3).

Estimates of natural recharge were taken from published reports by Anderson (1972) and Osterkamp (1973). Minor spacial redistributions were made in the model during the calibration period.

Recharge from infiltration of excess agricultural irrigation was estimated for those lands where measured irrigation water was applied. Initial values for potential recharge were developed by the DWR Office of Water Conservation and were based on estimated historic water application rates or pumpage and crop consumptive-use figures. These estimates were prepared for time periods: 1960-1969 and 1970-1979. For the period 1960-1969, potential recharge equivalent to 26 percent of the applied water was calculated, a value of 20 percent of the applied water was calculated for the period 1970-1979. This difference was due to increases in pumping lifts, power costs, awareness of water conservation and improved irrigation efficiencies on individual farms that occurred during the latter period.

Agricultural lands where net pumpage was calculated using crop type and consumptive-use factors were not assigned recharge values (refer to Pumpage section).

Industrial recharge was found to be significant only in the mines area because of water used in various mining processes, particularly in tailings pond disposal of waste material.

Assigned values range from 20 to 29 percent of pumpage and were taken from estimates derived by the Arizona Bureau of Mines. (Personal Communications, Arizona Bureau of Mines, 1972)

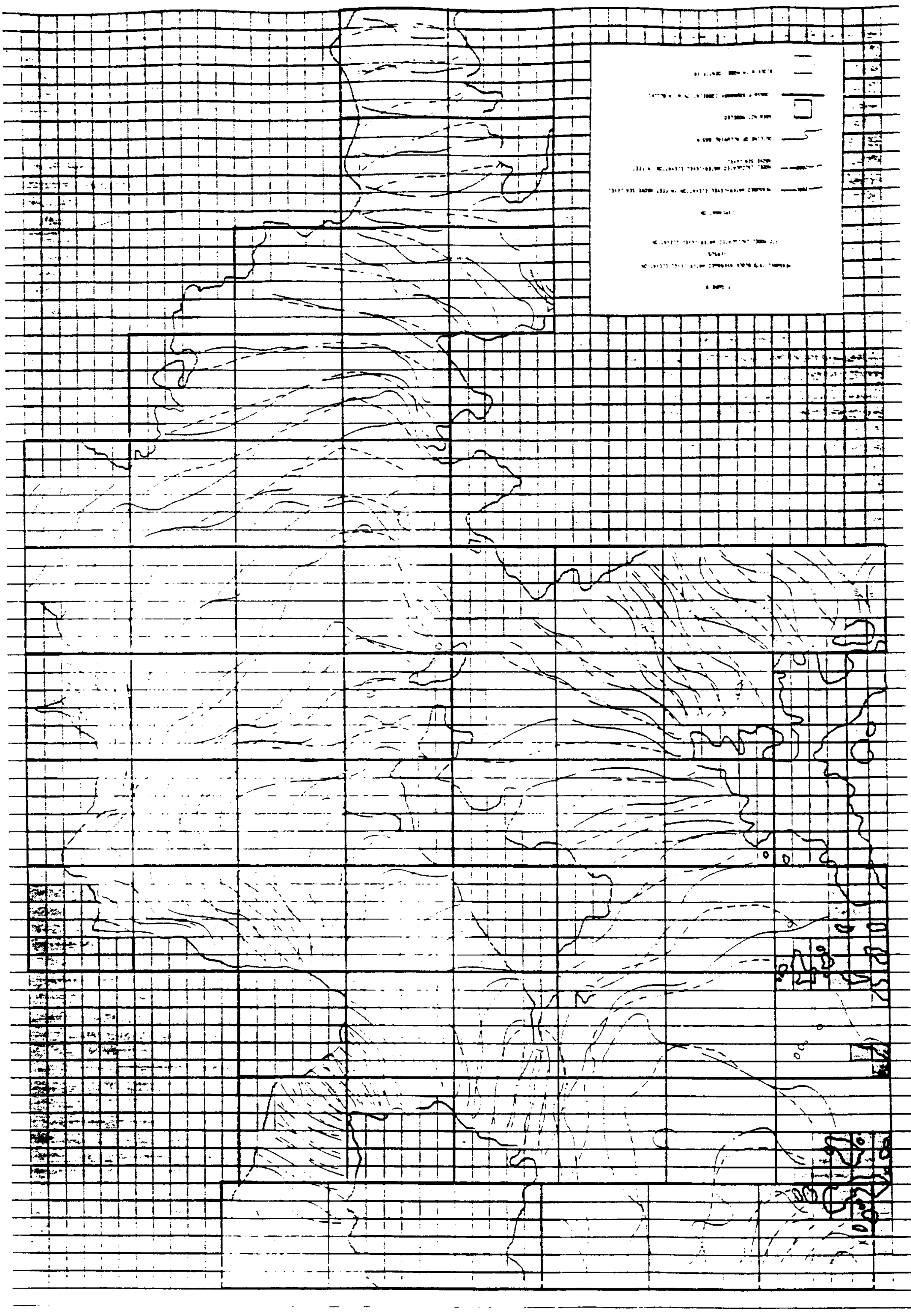
Municipal recharge occurs from releases of treated effluent. Effluent is discharged into the Santa Cruz River from sewage treatment plants at Roger Road and Ina Road. The Roger Road Plant has been treating effluent since 1951, Ina Road since 1977. Until 1973, the majority of effluent was sold to various farming customers. After 1973, the majority of treated effluent was released into the Santa Cruz River. The remainder has been sold to the Cortaro Water Users Association, Silver Bell Golf Course and Pima County's Arthur Pack Golf Course. The only other large scale treatment plant is located at the City of Tucson's Randolph Park. This treatment plant has been in operation since 1975 with all of the treated effluent being applied to the neighboring Randolph Park Golf Course.

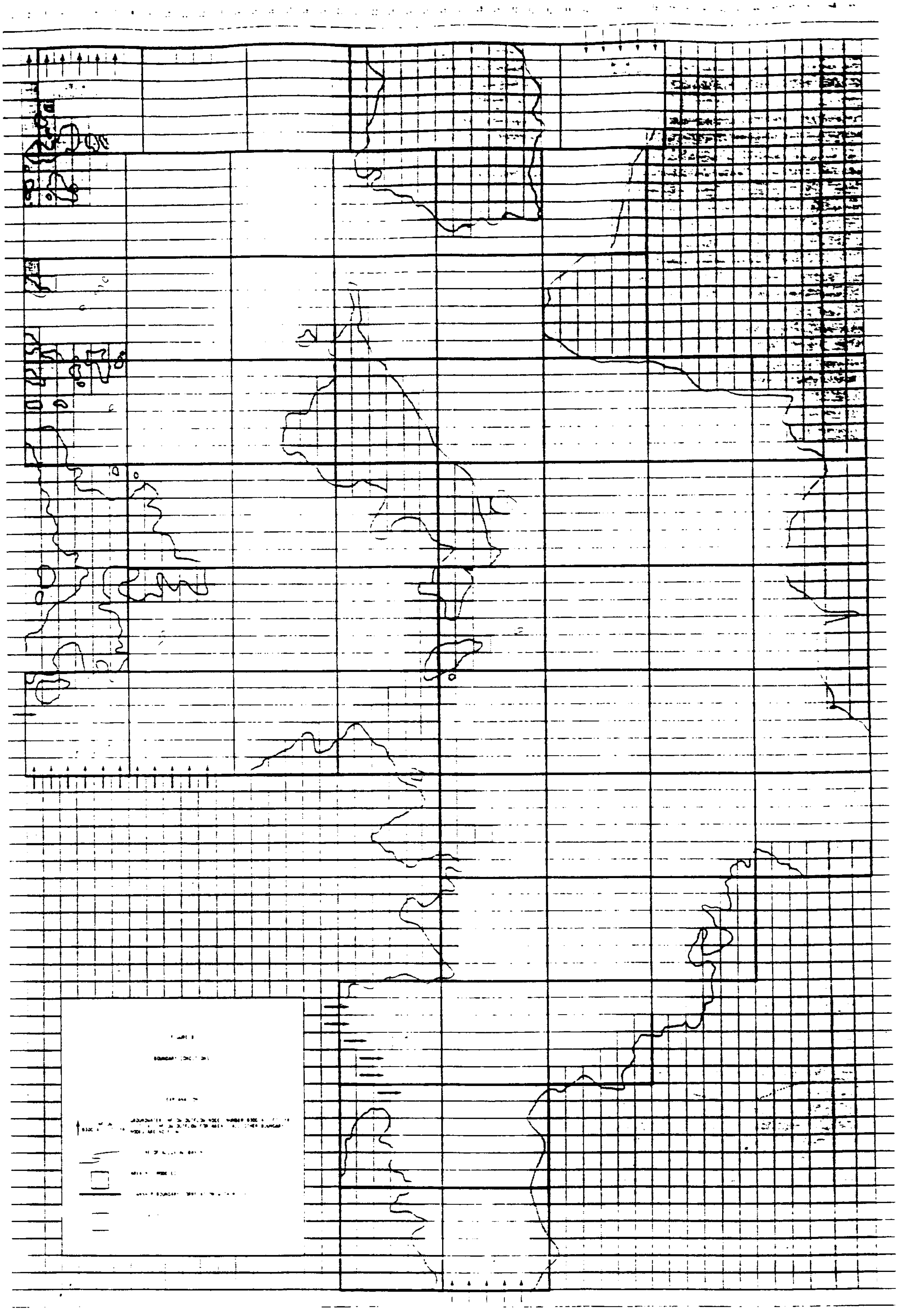
Recharge values from effluent released into the Santa Cruz River were based upon published infiltration values by Cluff, DeCook and Matlock (1972). This study provided infiltration rates for various reaches along the Santa Cruz River below the two treatment plants. It was first assumed that of the volume of effluent released, 80 percent would percolate to the water table. Flows were distributed throughout each reach until 80 percent of the total release was applied. However, through the calibration process, it was found that only about one-half of the infiltrated water may have actually reached the water table. Therefore, effluent was redistributed using 40 percent of the total released. Effluent that was sold to agricultural interests was recharged at rates developed by the Office of Water Conservation based on crop consumptive-use and historic application rates.

Boundary Conditions

Two types of boundary conditions were used in the USC/AVR model to simulate the natural boundary conditions, no-flow boundaries and specified flux boundaries. No-flow boundaries are those where groundwater inflows and outflows do not occur. Example of such boundaries are thick tight compacted clay layers, unweathered massive rock, faults that isolate the aquifer from other permeable strata, or groundwater divides (Boonstra, 1981). The model uses no-flow boundaries for two of these conditions, massive rock (i.e., mountain ranges) and a groundwater divide (see fig. 8). Specified flux boundaries were assigned where groundwater inflow and outflow occurred.

Flows (Q) at specified flux boundaries were calculated using transmissivity (T), node width (W), and hydraulic gradient (i) and the equation $Q = TiW$. These values matched fairly well when compared with the flow values given at these boundaries in published reports by Anderson (1972), Moosburner (1972) and Davidson (1973) and with recharge values used as model input data from the U.S. Army Corps of Engineer's Tucson Urban Study (unpublished). Comparison of these values allowed a range of values to be tried in the model to arrive at a reasonable calibration.





MODEL RESULTS

Calibration Results

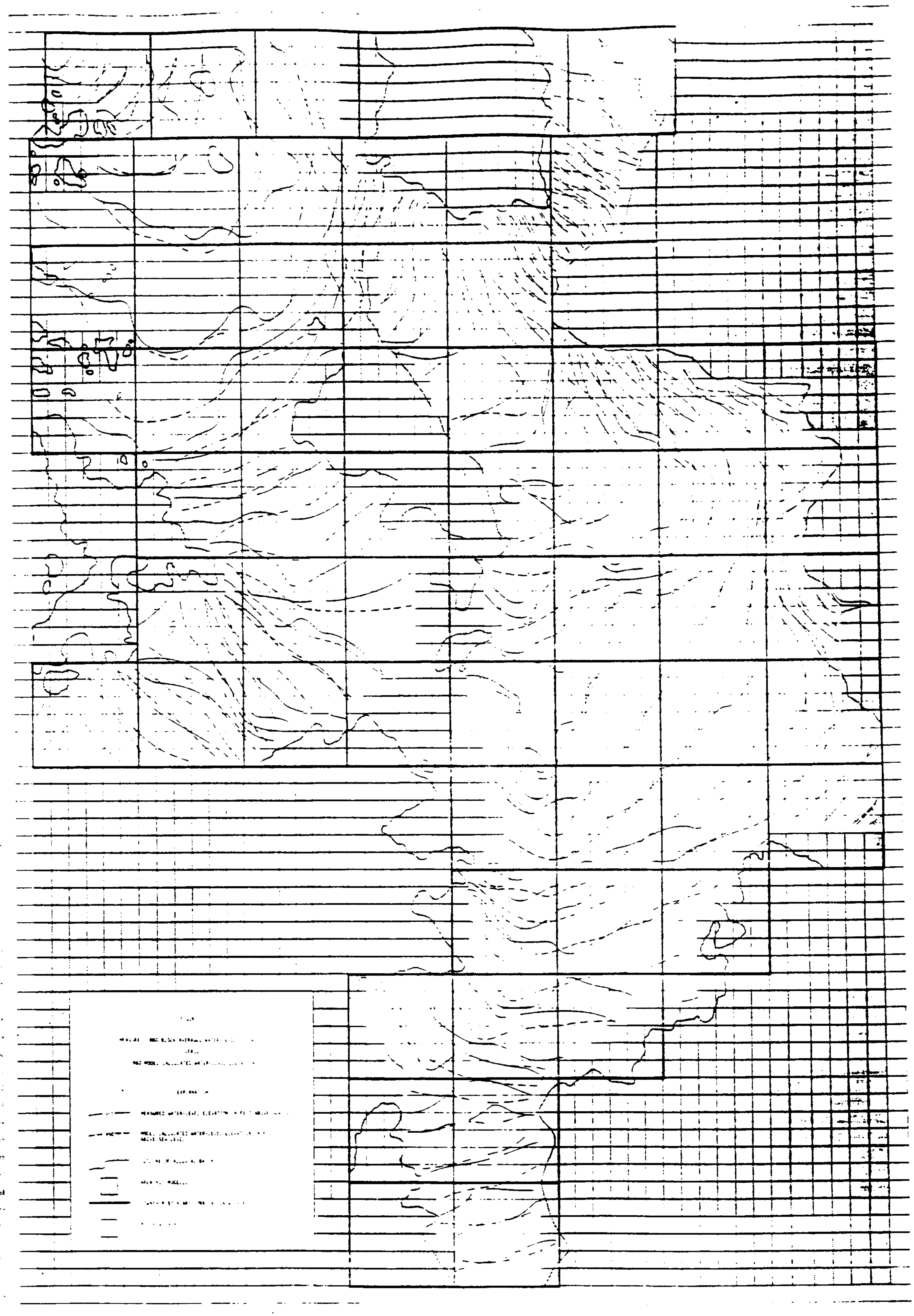
An initial calibration run for the 1960-1969 period was made prior to adjusting the input parameters. The average absolute difference was 27.4 feet. This run was followed by a series of documented calibration runs. For each subsequent calibration run, problem areas were isolated and attempts were made to reduce the absolute difference. This process first required verification of the input data, a check to see if the data being used had been input correctly. Generally adjustments were then made for any values which appeared to be abnormally high or low. As an example, a transmissivity value of 150,000 gal/day/ft with all surrounding values 50,000 gal/day/ft was replaced with an average of the surrounding values. If that only slightly improved the area, other data changes were made. Possible changes included redistribution of natural recharge, minor changes in transmissivity and/or specific yield, reduction in municipal recharge, adjustments in water-level elevations or elimination of nodes which upon closer inspection seemed to be outside the main aquifer. Pumpage values were not changed.

This procedure continued until reasonable changes no longer made a positive change. The final average absolute difference for the modeled area after more than 40 runs was approximately 16.8 feet (see Figure 9).

Verification Results

The next step was a verification of the parameters used in the calibration run. The verification run (1970-1979) used the calibration period data for natural recharge, transmissivity, specific yield and boundary conditions and the data for pumpage, agricultural, municipal and industrial recharge data, and measured beginning and ending water levels for 1970-1979 period.

Again, an initial verification run for the 1970-1979 period was made without adjustments to the input parameters. The average absolute difference was 20.1 feet. A few minor adjustments were made to the input parameters. The most significant of these changes were to the water-level elevations. During this phase of the modeling, it became apparent perched water-level elevations were originally contoured with the regional system. After minor adjustments were made to the parameter used in the verification run, the end result was an average absolute difference of 17.3 feet (see fig. 10). This difference was slightly greater than the calibration run, possibly due to the apparent increasing influence of the model's boundaries. Other possibilities, such as manifestations of vertical flow components, and decreasing transmissivity and specific yield with declining water levels may account for this slight increase.



The total difference (see table 4) was distributed as follows:

Range of Difference (in feet)	Percentage of Total Nodes
0-5	21%
6-10	18%
11-15	16%
16-20	12%
21-25	10%
26-35	12%
>35	11%

SENSITIVITY ANALYSIS

Methodology

The configuration of the water table surface predicted by the model may be more strongly affected by a change in one data parameter than by a similar change in another. Also, changes of equal magnitude in a particular parameter at different locations will have different effects. The degree of change in water levels calculated by the model due to an artificial change in a data parameter is termed sensitivity.

Sensitivity analysis is a method of measuring the effects of poorly known parameters throughout the model or in specific locations. The USC/AVR model was analyzed for sensitivity in two ways. One was to multiply specific yield or transmissivity in each node of the model by the same percentage and observe the effect of this change on calculated water levels. The other way was to modify one parameter in a particular location, while holding the other model parameters and the review parameter in other locations the same as in the final verification run. The effects on calculated water levels of this change were then observed. If the effects are large, the parameter needs to be well defined. Additional field data can be obtained or existing data can be reviewed to improve the parameter estimates.

The effects of ±20% variations in transmissivity or specific yield throughout the model on calculated drawdowns for the period 1970 to 1980 are shown along column 13 in Avra Valley and along

Figure 11 - Effects of varying the aquifer transmissivity and specific yield on model-calculated drawdown in Avra Valley

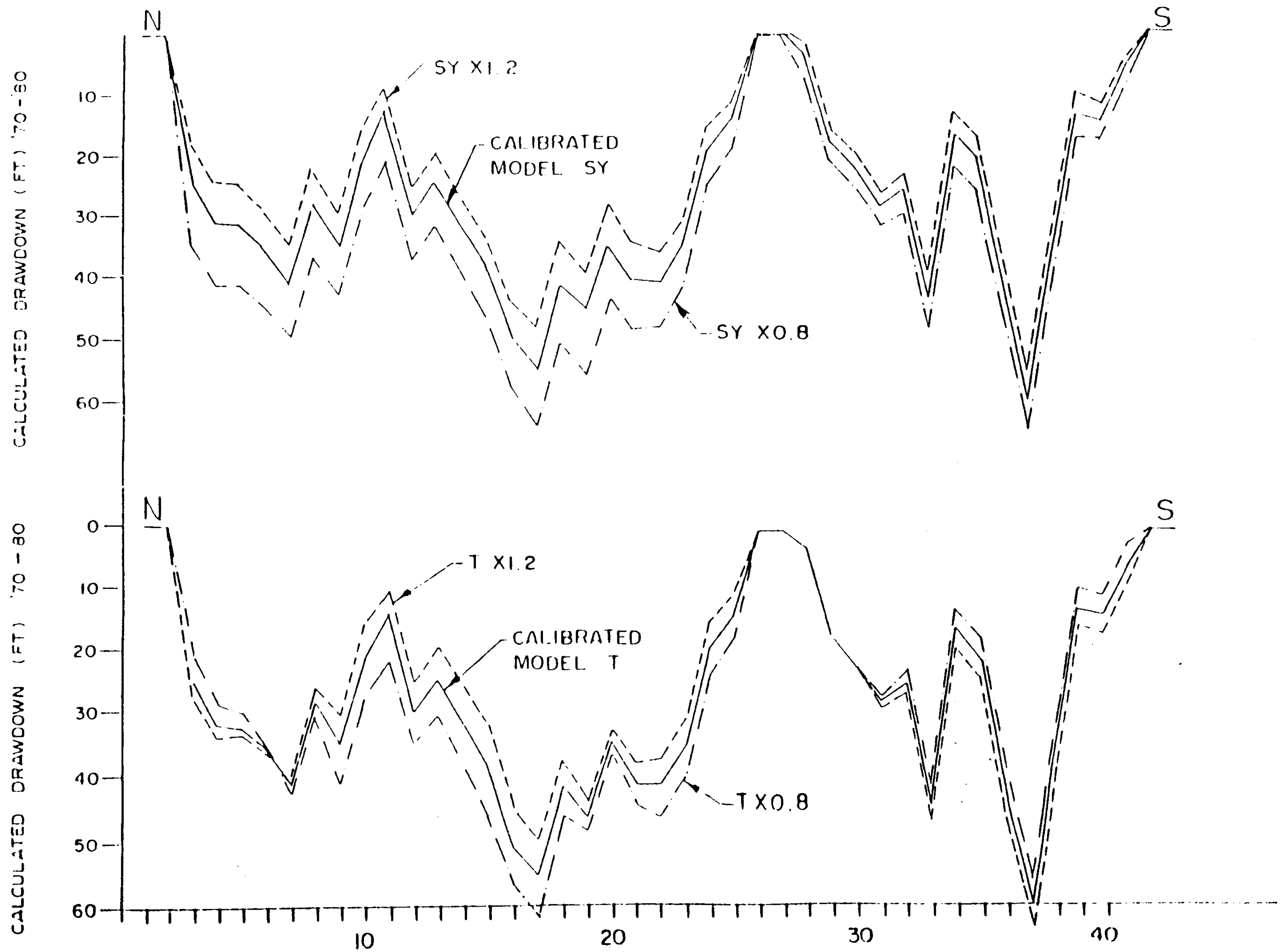
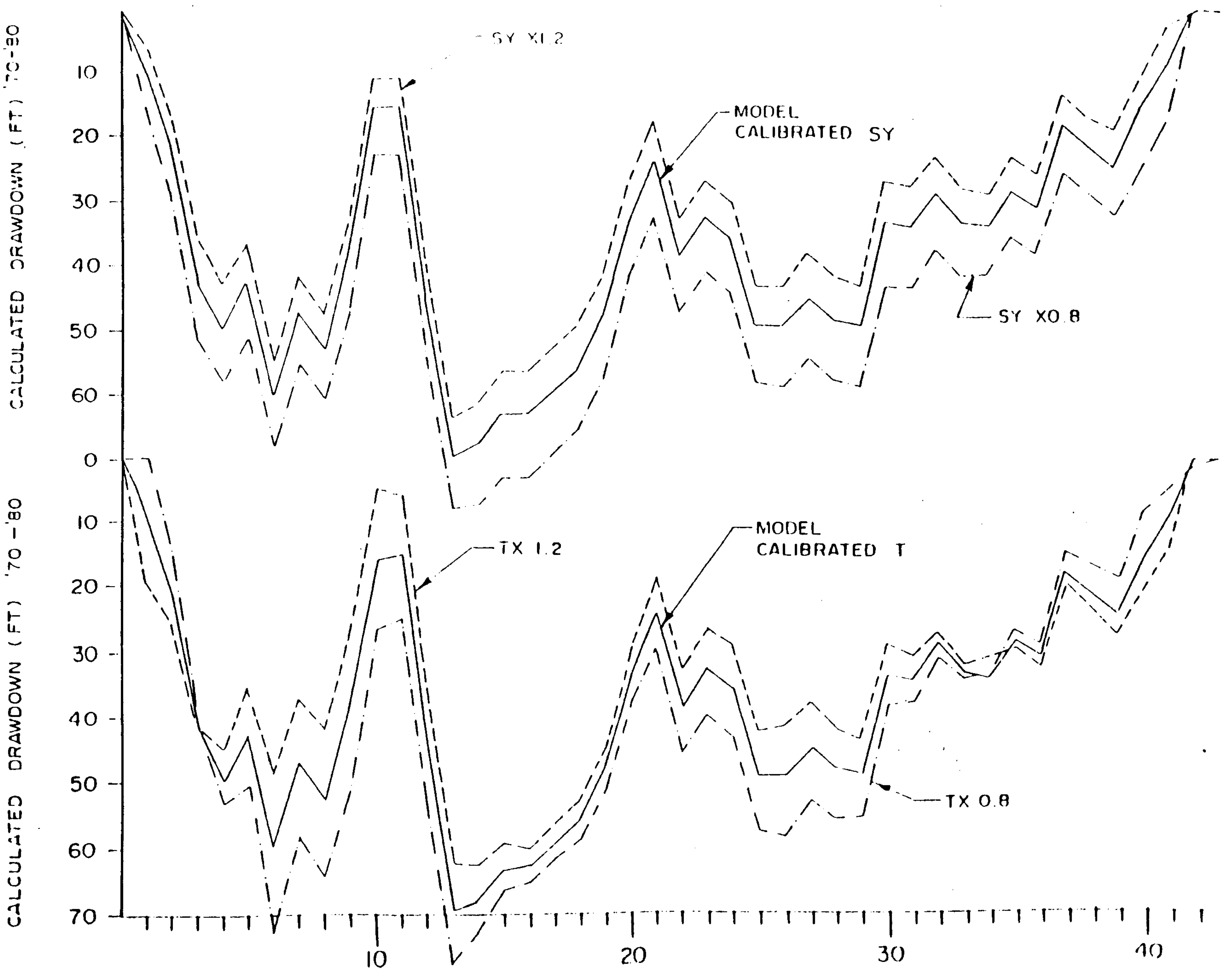


Figure 12 - Effects of varying the aquifer transmissivity and specific yield on model-calculated drawdown in the Upper Santa Cruz Basin.



column 33 in the USC basin in Figures 11 and 12. The sensitivity of calculated water levels to ±20% variations in specific yield or transmissivity is generally small and dependent on location within the model. In the Cortaro-Marana and Tucson areas, ±20% specific yield variations have a larger effect than ±20% transmissivity variations because these areas are undergoing large scale storage depletion. Water levels in some areas of the model are more sensitive to ±20% transmissivity variations because movement of water is dominant over storage depletion. Analysis of Figures 11 and 12 indicates that the complex distributions of lithology, boundaries, pumpage, and recharge cause sensitivity to vary throughout the modeled area.

To determine the effects of scant data for estimating the parameters of transmissivity, specific yield, and natural recharge in particular locations, a sensitivity analysis was made for each model parameter. The methodology used for the transmissivity and specific yield analyses was developed by Boggs (1980) and has been applied by the U.S.G.S. (Matlock, 1981). A modified methodology used for natural recharge will be explained later. Specific areas of interest, or sensitivity zones, were selected within the modeled area based on boundary conditions, hydrogeology, recharge and pumpage. Next, a ten year base run of the model was made to determine the calculated 1980 water levels in each zone. Then, the parameter under review was uniformly changed throughout a zone, while the other model parameters and the review parameter in the other zones were held constant at their initially calibrated values. The model was again run for a ten year period to calculate the new 1980 water levels and the changes in water levels from the initial calibration to the 1980 level in all the zones were compared. An area-weighted average water-level change, called the sensitivity coefficient (Bn), was calculated for each zone. The procedure was repeated for each zone, and the sensitivity coefficients were tabulated into a sensitivity table. Because all zones were of equal size and shape and the parameter within the zones was modified by the same percentage, the coefficients calculated can be compared and evaluated. Zones in which a change in a parameter produced the largest effect on water levels throughout the model are the areas where accurate input data or estimates of the parameter are most essential for proper calibration of the model.

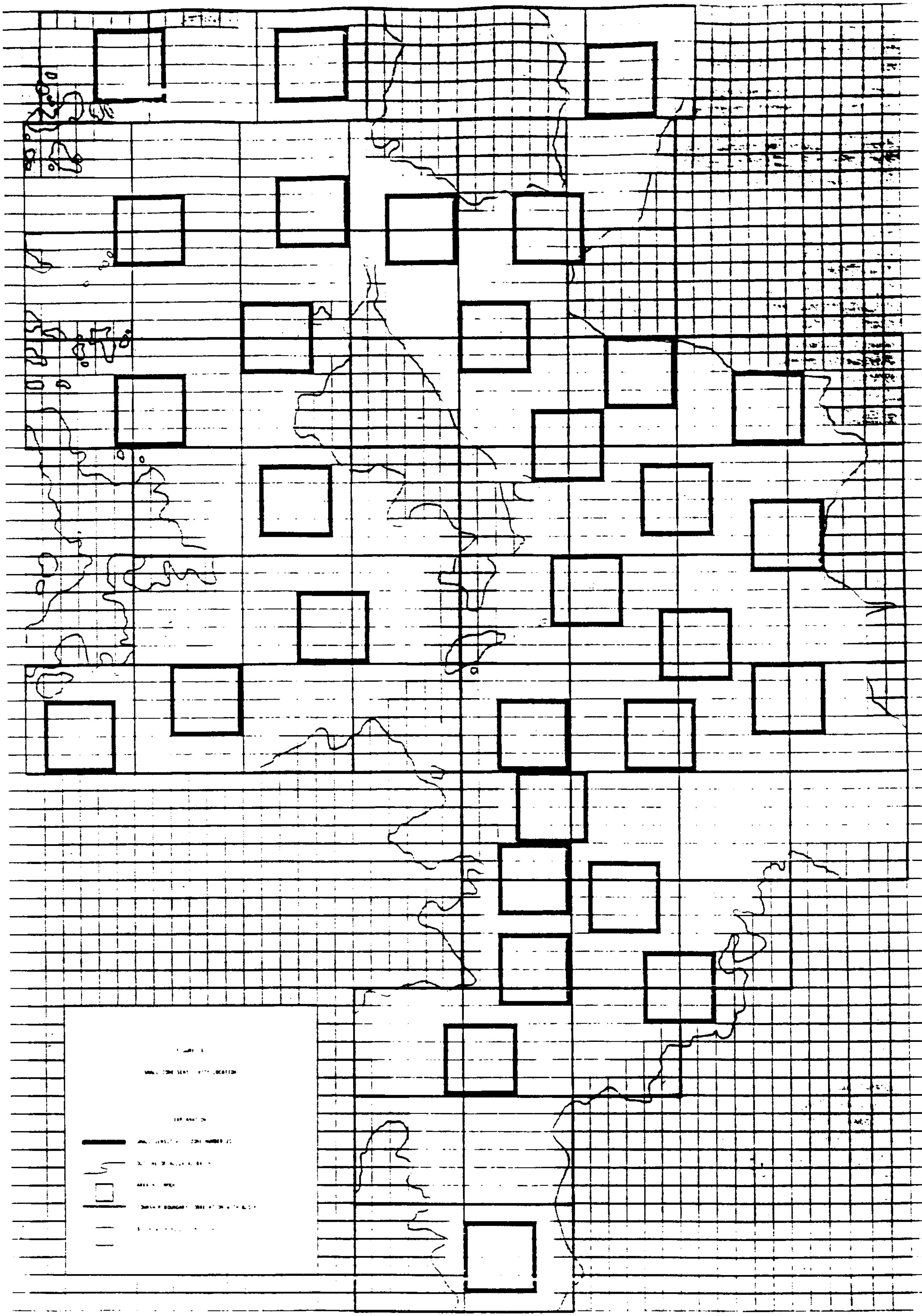
Specific methodologies and the results of the sensitivity analyses for each parameter under review are briefly described in the following sections.

Transmissivity and Specific Yield Sensitivity Analyses

An increase of 50% was chosen for both the transmissivity and specific yield analyses. The effect of an increase in transmissivity or specific yield in a zone will obviously be different from the effect of a decrease in transmissivity or specific yield in that same zone. However, the relative degree to which a specific zone can influence the flow field or provide water to or from storage will be indicated by either an increase or a decrease approach if the changes are uniformly made in each zone.

Thirty zones, each 16 square miles in area, were chosen throughout the model (see fig. 13). Areas between the zones were assumed to have smooth horizontal flow so that sensitivities could be interpolated between zones.

The sensitivity coefficients calculated for all the zones in the transmissivity analysis are shown in the sensitivity table (table 5). The largest sensitivity coefficient was 11.4 feet in zone #19 in the area where the Canada del Oro Wash joins Big Wash. The relatively high sensitivity to a transmissivity change in this area is due to the fact that the aquifer narrows, regional flow is converging, and steep hydraulic gradients predominate. Other significant sensitivity coefficients were observed in zones #1, 2, 3, 13, 16 and 17 at inflow areas of major drainages, zone #24 at the outflow area of the model, and zones #4, 6, 7, 8 enclosing the mines area and zones 15 and 23. These are all areas with relatively steep hydraulic gradients. The changes in water levels predicted by the model due to a change in transmissivity in a typical zone are shown in figure 14. For most of the zones, the change in transmissivity produced less than one foot of change in water levels and therefore water levels across the model were unaffected by a single local transmissivity change.



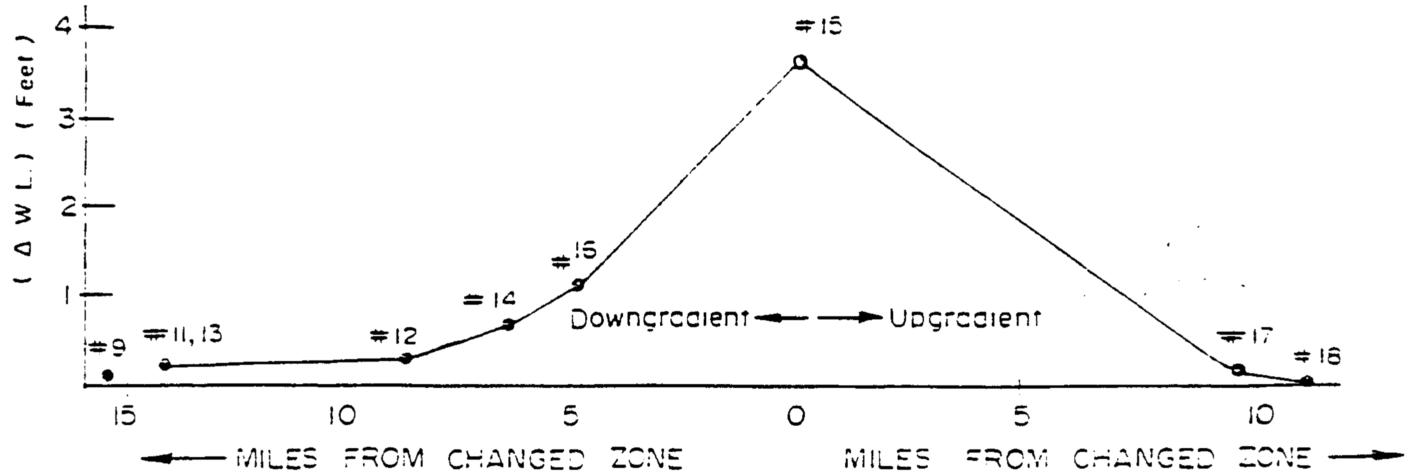


Figure 14 Average Zonal water level change (Bn) due to a 50% increase in transmissivity in Zone #15 vs. distance.

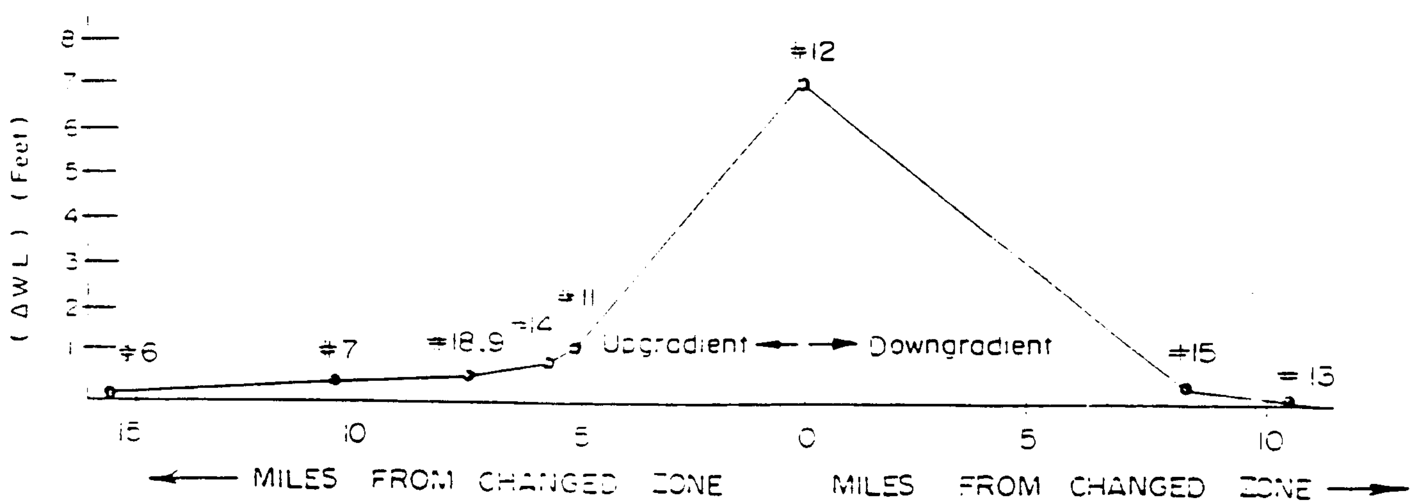


Figure 15 Average Zonal water level change (Bn) due to a 50% increase in specific yield in Zone #12 vs. distance.

The same zones and methodology were used in evaluating specific yield. The results of the specific yield analysis are presented in the sensitivity table (see table 6). The largest sensitivity coefficient was 11.3 feet in zone #24 which encloses the Santa Cruz River channel at the model's outflow boundary. Zones #2, 4, 6, 7, 8, 12, 15, 20 along the Santa Cruz River and zones #25, 26, and 30 in Avra Valley also showed significant sensitivity coefficients. These zones all contain areas of intensive pumping. Zones #13, 16, and 23 are additional examples of significant sensitivity to modifications in specific yield. The large water level changes in these zones are probably due to the location of the zones in areas of mountain front recharge originating from the Santa Catalina, Tanque Verde, Rincon, and Tortolita Mountains. Areas of intensive pumping represented the most sensitive zones to changes in specific yield. The changes in water levels predicted by the model due to a change in specific yield in a typical zone are shown in figure 15. For most of the zones, water levels across the model were generally unaffected by a single local change in specific yield.

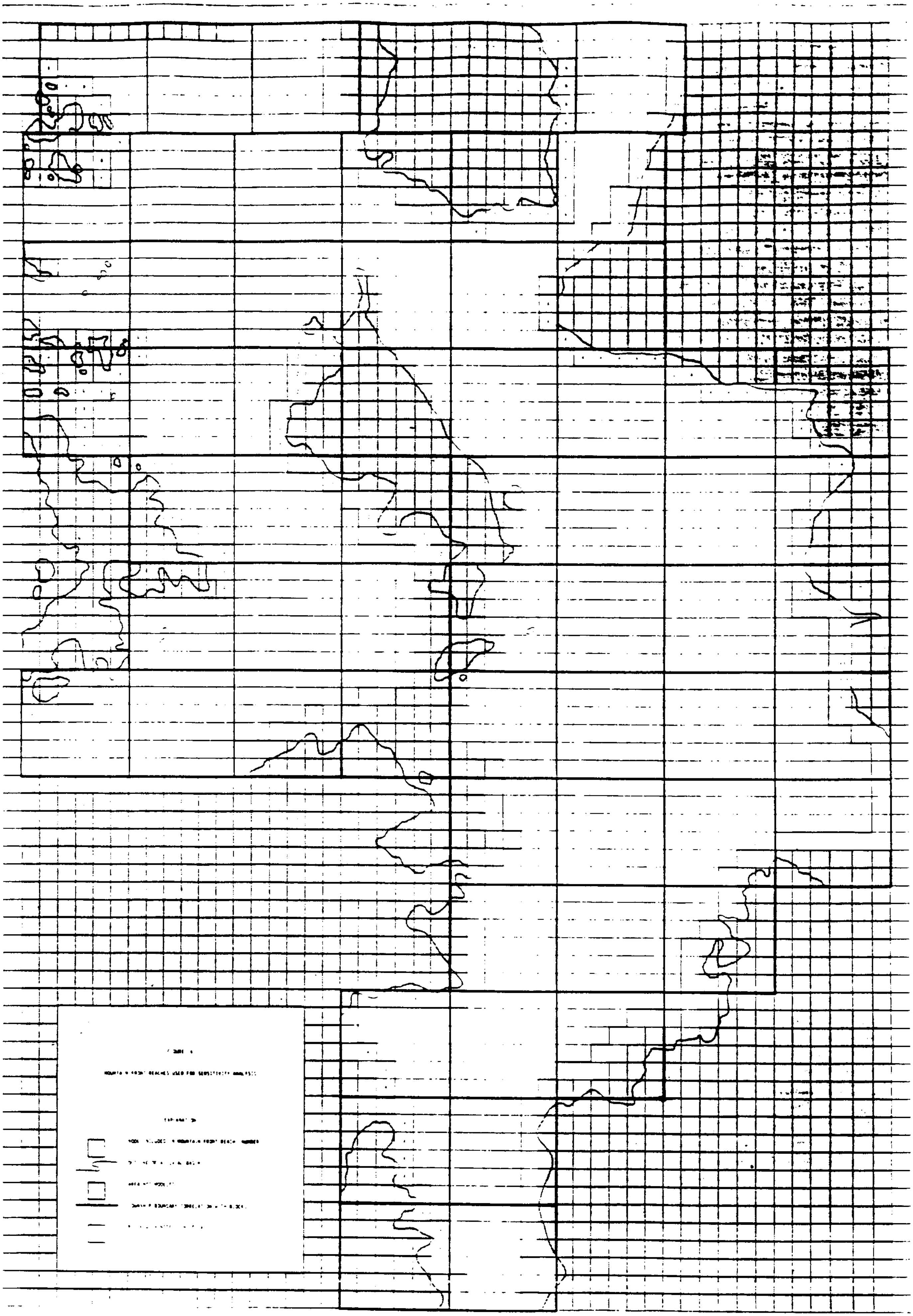
The effect of changing transmissivity or specific yield over larger areas was also analyzed. A 50% increase in the parameters was made in 15 zones, each 64 square miles in area, located throughout the modeled area. The same sensitivity analysis methodology previously described was performed and the effects on the water levels observed. The sensitivities of a few small zones, eg. the Canada del Oro Wash, were not detected in the large zone analysis. However, the magnitude and geographic distribution of the sensitivity coefficients were generally the same for the large zone analysis as for the small zone analysis. Water levels in most of the surrounding zones were unaffected by a 50% increase in transmissivity or specific yield in one large zone.

Natural Recharge Sensitivity Analyses

Areas of the model in which water levels were most affected by stream channel and mountain front recharge were located with sensitivity analyses. Mountain front and stream channel recharge areas were divided into short reaches for the purpose of investigating the sensitivity of the model response to the distribution of recharge.

In the mountain front recharge analysis, fourteen lengths of mountain front approximately 20 miles in length were selected (see fig. 16). The model was run 10 years to provide the calculated 1980 water levels in each of the sensitivity zones. Next, the mountain front recharge estimates in reach #1 were set to zero. The model was again run for a ten year period to calculate the new 1980 water levels. An area-weighted average water level change due to the modification in reach #1 was calculated for each of the thirty sensitivity zones in the model. The procedure was repeated, making a similar modification in recharge in each reach separately and comparing the effects upon the water table.

The results of the mountain front recharge sensitivity analysis showed that the largest sensitivity coefficient was 17.4


MOUNTAIN FRONT REACHES USED FOR SENSITIVITY ANALYSIS
EXPLANATION

feet. This sensitivity was observed in zone #16 near Sabino Canyon and was caused by the removal of mountain front recharge from reach #4. The model was also sensitive to a significant degree in zones at the outlet areas of major drainages such as the Canada del Oro Wash, Agua Caliente Canyon, Tanque Verde Canyon, and Madera Canyon. The remaining mountain front reaches had negligible effects on water levels. The changes in water levels predicted by the model due to a change in the mountain front recharge in two reaches are shown in figure 17. For zones at a distance greater than 10 miles from the mountain front, the sensitivity due to the removal of recharge was negligible.

Using similar methodology, areas of the model in which water levels are most affected by stream channel recharge were located by sensitivity analyses. Nine reaches of stream channel were chosen for analysis (see fig. 18). Stream channel recharge estimates were set to zero in each reach of stream channel and the effects on water levels in all zones of the model were observed. The largest sensitivity coefficient was 13.9 feet in zone #24 near Red Rock due to the removal of stream channel recharge from the Santa Cruz River along reach #7. Water levels in zones near the Tubac and Tanque Verde areas were also strongly affected by the removal of stream channel recharge. The changes in water levels predicted by the model due to removal of stream channel recharge from two reaches are shown (see fig. 19). For zones at a distance greater than 10 miles from the stream channel, the sensitivity due to removal of recharge was negligible.

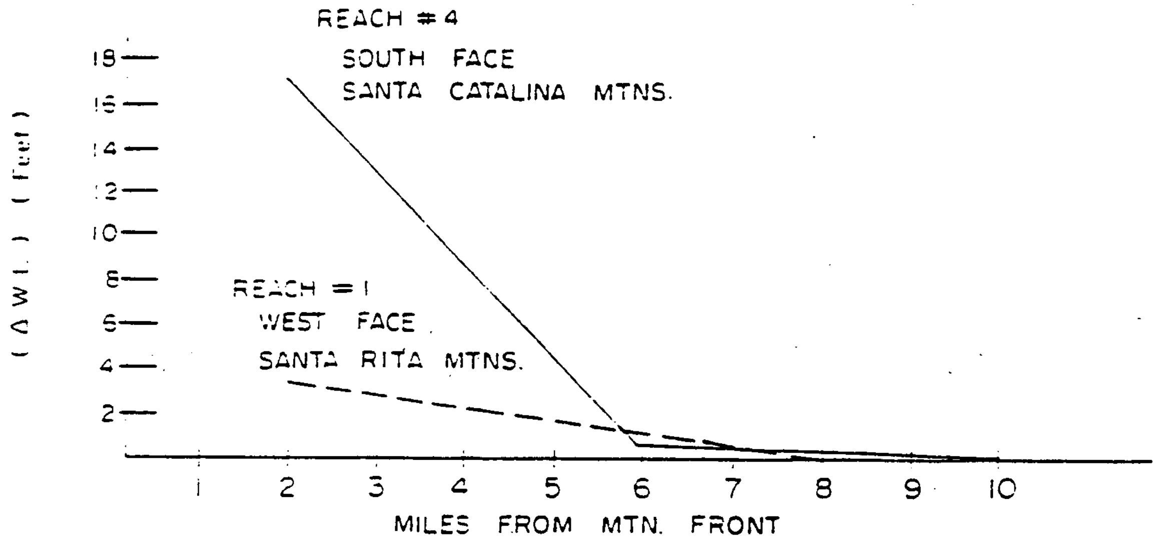


Figure 17 Graph of average zonal water level change (Bn) due to the removal of mountain front recharge in one reach vs. distance from the mountain front.

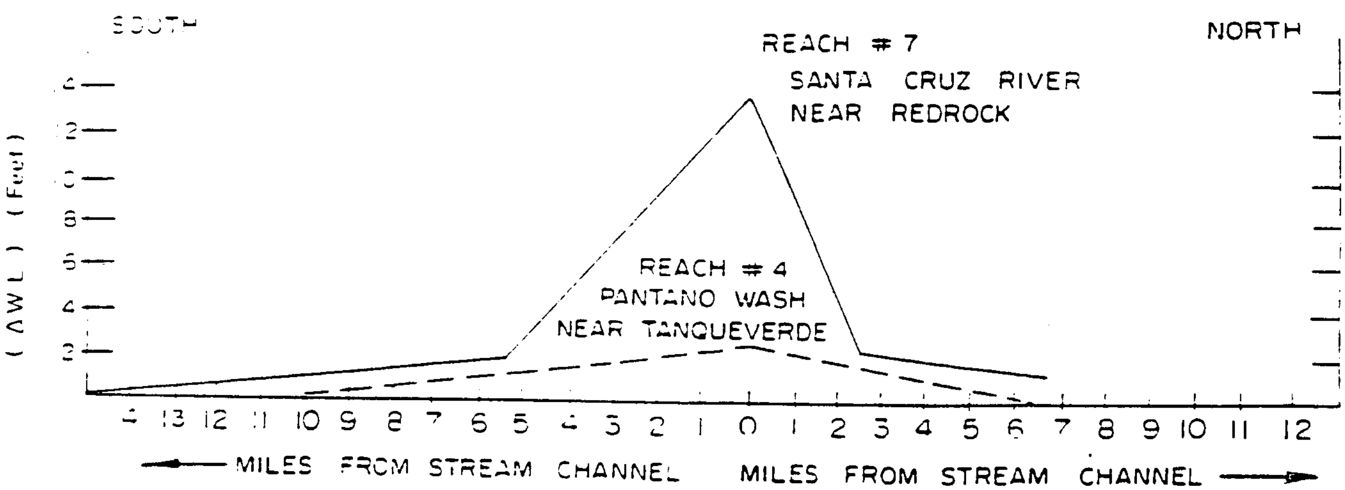
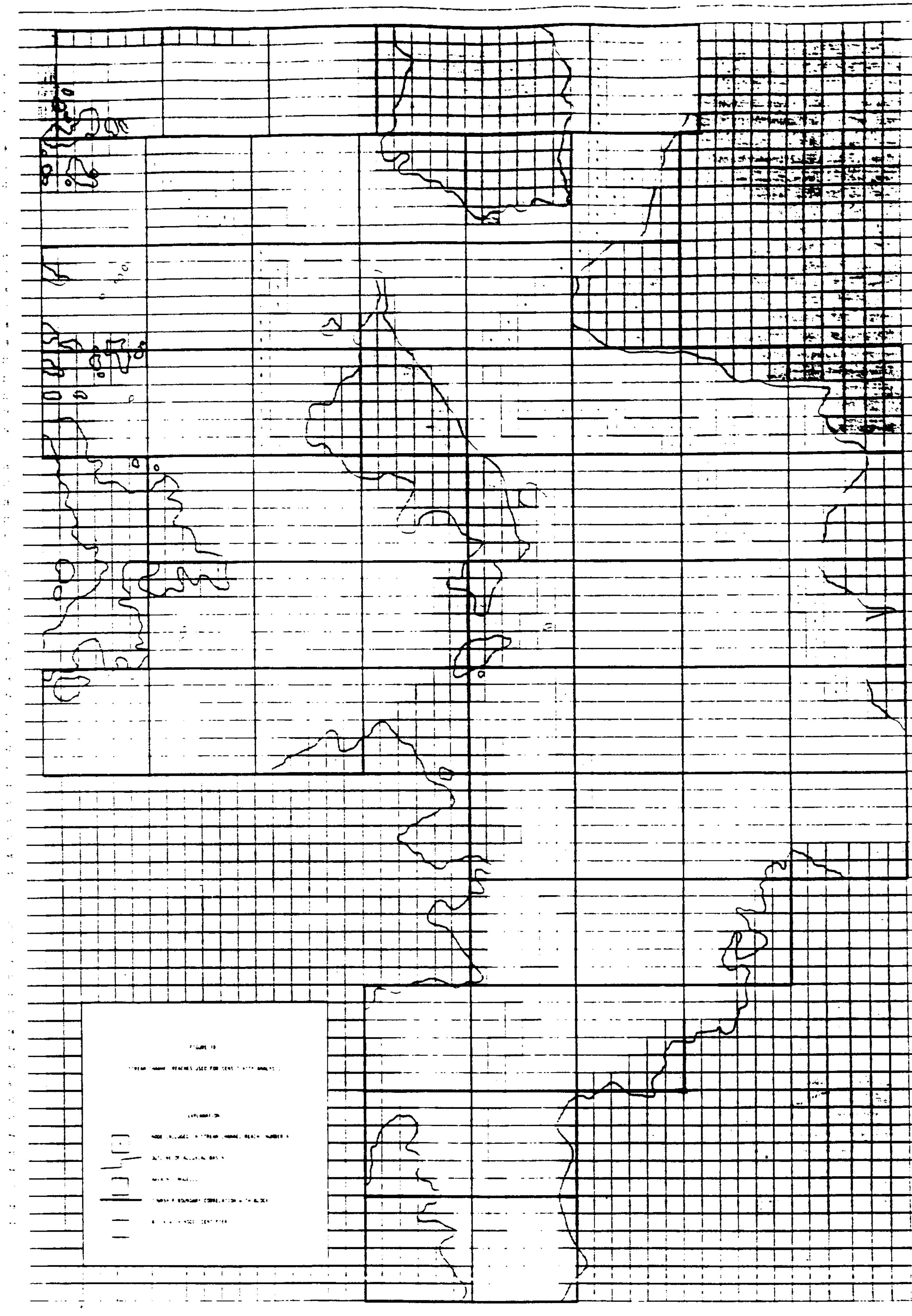


Figure 19 Graph of average zonal water level change (Bn) due to the removal of stream channel recharge from one reach vs. distance from the stream channel.



SUMMARY

Sensitivity analyses located areas of the USC/AVR model in which the effects of scant data for estimating transmissivity, specific yield, and natural recharge are greatest. Water levels in areas of converging flow or inflow and outflow at the edges of the model were most sensitive to transmissivity. Water levels in areas of intensive pumpage were most sensitive to specific yield. Water levels in areas adjacent to large mountain masses, such as the Santa Catalina Mountains, were most sensitive to mountain front recharge and water levels in the areas of large river channels, such as the Santa Cruz River near Red Rock, were most sensitive to stream channel recharge.

Sensitivity analyses quantified general ideas about hydraulic properties of the USC/AVR area. Small zone analyses located specific areas of sensitivity that large zone analyses were unable to locate such as the sensitivity of water levels to transmissivity in the Canada del Oro area. Sensitivity analyses thus indicated areas of the USC basin and Avra Valley that deserve closer study.

MODEL CAPABILITIES

The model is complemented by a comprehensive data base which can be accessed to identify estimates of pumpage and recharge by type, location and year. The model data base can also be searched to provide useful summaries of transmissivity, specific yield and historic water-level elevation values. The data base will provide a basis for extrapolation of the data as desired for use in projecting future conditions. The data base can also provide initial aquifer parameters for various hydrologic studies of the area and through cross indexing, lead to the actual data used to develop the parameters for a specific block or area.

Model projections can be run to compare the impacts of a variety of **alternative development and management plans.** This will enable the DWR and other agencies to consider various alternatives and choose the most practical course for management of groundwater resources in the area.

The USC/AVR model can be used for long-term water supply projections for the portions of the model that have a good historical match along with a supportive data base. The data generated by the USC/AVR study satisfies the background information needed for many large scale one hundred year water supply predictions. Groundwater consultants, as well as DWR hydrologists, can utilize the study data to assist in making water supply predictions for large subdivisions.

The USC/AVR model can also be used in designing large scale pumping patterns for municipal or agricultural well fields by determining future water-level decline under various pumping regimes. Installation of large scale well fields can be simulated to determine long term interference effects on other groundwater users in the immediate vicinity.

RECOMMENDATIONS

The USC/AVR data base needs to be continually updated with any new hydrologic and geologic data which becomes available. Using the updated data base, future verification periods can be simulated, further refining the acceptable difference of the model and improving adequacy.

One important source of new data will be metered pumpage. The Groundwater Management Act of 1980 requires that pumpage from all non-exempt wells (wells with installed pump capacities greater than 35 gallons per minute) be reported annually to the Director of the Department of Water Resources. With more accurate pumpage data, parameters such as recharge and specific yield that are not readily measured can be quantified more accurately.

Additional data regarding the three-dimensional nature of the USC/AVR aquifer system are necessary. For example, better delineation of changes in hydraulic head with depth would begin to define areas where significant vertical flow components could occur in the system in response to stress.

Changes in transmissivity and specific yield with depth also need to be identified to allow changes of these model parameters as water levels decline. Time delays affecting recharge must also be examined further to see the possible effects of changes in agricultural water use and the occurrence of large floods. Information on these relatively poorly quantified items should have a high priority in future data collection programs.

CONCLUSION

The Upper Santa Cruz/Avra Valley model is a calibrated and verified two-dimensional digital finite-difference groundwater model of the Upper Santa Cruz basin and Avra Valley located in southeastern Arizona. Complimenting the model study is a comprehensive data base which includes pumpage, recharge, water-level elevations and aquifer parameter data for the period 1960-1979.

The USC/AVR model has adequately simulated the historic aquifer conditions for two independent ten year periods (1960-1969 and 1970-1979) based on an acceptable difference criteria of ±20 feet.

A sensitivity analysis performed on the model has shown a relative lack of sensitivity to the aquifer parameters of transmissivity and specific yield. Further data collection efforts should concentrate on more precise pumpage information and improved water-level elevations within the less developed areas. An additional simulation period should accompany these data aquisitions to verify the assumptions used in the two previous simulations.

GLOSSARY OF TERMS

Definitions are modified from Lohman and others (1972).

Aquifer

A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Groundwater Divide

A ridge in the water table or other potentiometric surface across which groundwater does not flow.

Groundwater Model

A mathematical representation of a groundwater flow system.

Head

The height above a standard datum of the surface of a column of water that can be supported by the pressure at a given point in an aquifer. In this report, head is referred to the National Geodetic Vertical Datum of 1929.

Hydraulic Conductivity

The rate at which water is transmitted through a unit cross-sectional area of an aquifer under a unit hydraulic gradient. It describes the ability of the aquifer material to transmit water, and it may have substantially different values in the horizontal and vertical directions.

Hydraulic Gradient

The change in static head per unit of distance in a given direction.

Recharge

The processes by which water enters an aquifer.

Specific Yield

The ratio of (1) the volume of water which a rock or soil, after being saturated, will yield by gravity to (2) the volume of the rock or soil.

Storage

In groundwater hydrology, this term refers to water retained in a groundwater reservoir.

Storage Coefficient

The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Transmissivity

The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It describes the ability of the entire thickness of an aquifer to transmit water. Transmissivity is the product of hydraulic conductivity and thickness of the aquifer.

Water-Level Elevation

Elevation of the water level above mean sea level. See also head.

Water Table

The water surface in an unconfined aquifer at which the pressure is equal to atmospheric pressure. It is the water level in wells that penetrate the uppermost part of an unconfined aquifer.

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