Guide for Data Collection to Calibrate a Predictive Digital Ground-Water Model of the Unconfined Aquifer in and near the City of Modesto California

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City of Modesto

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Factors for converting English units to metric units (*SI*) are given below to four significant figures. In the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	*Multiply by:*	*Metric (SI)*
acre-ft (acre-feet)	1.234×10^{-3}	hm^3 (cubic hectometres)
ft (feet)	3.048×10^{-1}	m (metres)
ft/s (feet per second)	3.048×10^{-1}	m/s (metres per second)
ft^2/d (feet squared per day)	9.290×10^{-2}	m^2/d (metres squared per day)
gal/min (gallons per minute)	6.309×10^{-2}	ℓ/s (litres per second)
(gal/min)/ft (gallons per minute per foot)	2.07×10^{-1}	(ℓ/s)/m (litres per second per metre)
in (inches)	$2.54 \times 10^{+1}$	mm (millimetres)
lb/in^2 (pounds per square inch)	6.895	kN/m^2 (kilopascals per square metre)
mi (miles)	1.609	km (kilometres)
mi^2 (square miles)	2.590	km^2 (square kilometres)

GUIDE FOR DATA COLLECTION TO CALIBRATE A PREDICTIVE DIGITAL GROUND-WATER MODEL OF THE UNCONFINED AQUIFER IN AND NEAR THE CITY OF MODESTO, CALIFORNIA

By R. W. Page

ABSTRACT

The city of Modesto encompasses about 12 square miles (31 square kilometres) in the northeastern part of the San Joaquin Valley, Calif. The model described in this report encompasses about 542 square miles (1,404 square kilometres).

In the Modesto area, ground water occurs in an unconfined aquifer, a confined aquifer, both of which are composed of unconsolidated materials, and a consolidated-rock aquifer. Only the unconfined aquifer was modeled.

In order to model the unconfined aquifer, several simplifying assumptions concerning hydrologic conditions in the ground-water basin and the flow therein were made. These assumptions permitted solutions to the equation of flow. Prior to using the iterative digital model, use was made of a program that computed the net rate of recharge and discharge under steady-state conditions. The model was then modified until reasonable values of recharge and discharge were computed.

Testing of the model indicated that simulated water levels were especially sensitive to transmissivity, storage coefficient, the return of irrigation water, and riverbed hydraulic conductivity; among the parameters that affected water levels least were the vertical hydraulic conductivity and specific storage of the confining bed, the so-called E-clay.

A special effort should be made to accurately determine those parameters to which the model is especially sensitive in order to improve the predictive accuracy of the model.

INTRODUCTION

Location and General Features

The city of Modesto encompasses about 12 mi^2 (31 km^2) along and near the uolumne River in the northeastern part of the San Joaquin Valley (fig. 1). t has a population of about 68,000 (1970 census) and is the seat of tanislaus County, population 195,000.

Agriculture is the mainstay of the economy in the county, and during 1970 he value of agricultural production was nearly $232 million (Security Pacific ational Bank, 1971, p. 5). As a consequence of agricultural development, the ajor industries in Modesto are canneries, wineries, dairies, meat and poultry rocessing plants, and frozen-food plants. Other industries include manufacuring of machinery and packaging materials, and metal fabrication.

In 1972, water for the city and immediate area was supplied from 45 city ells, 49 wells of a private water company, and many privately owned domestic nd industrial wells. The area that will be serviced in the future by Modesto s shown in figure 1.

In the summer, the climate is characterized by low relative humidity, igh temperature, and a small amount of precipitation; in winter, it is haracterized by higher relative humidity, lower temperature, and moderate recipitation. The mean annual precipitation in the Modesto area is about 2 in (300 mm); 87 percent of it occurs from October through May.

Purpose and Scope

The purpose of this report is to provide information to be used as a uide for subsequent collection of geologic and hydrologic data required to alibrate a digital model of the ground-water system supplying the city of odesto. The scope of this study includes: (1) Using a digital-computer rogram to model the ground-water basin in and near the city of Modesto; and 2) using that model to determine the effect of change in any given hydrologic arameter on water levels generated by the model. This is the third report Page, 1972; Page and others, 1974) prepared by the U.S. Geological Survey in ooperation with the city of Modesto.

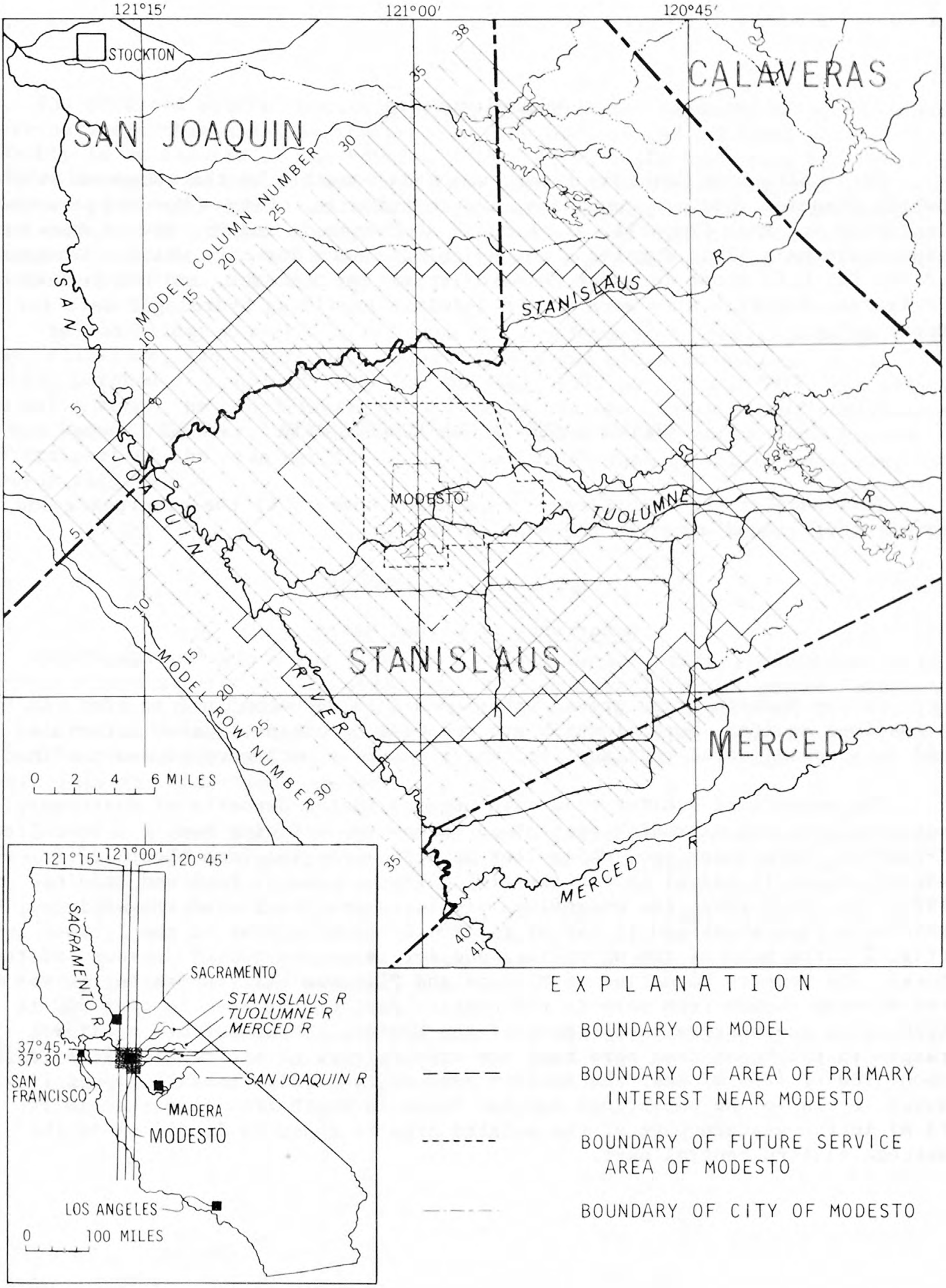


FIGURE 1.--Index map and grid showing nodal network, boundary of model, area of primary interest, and boundary of future service area.

Acknowledgments

Data collection for this report was made possible by the cooperation of public agencies, private companies, and individuals. City of Modesto personnel including Mr. Ross Campbell, Mr. Richard A. Hosegood, and Mr. Edward Ames were especially helpful in supplying the hydrologic data for city wells. Personnel of the Del Este Water Co., the Modesto Irrigation District, and the Turlock Irrigation District also were very helpful in providing hydrologic data for their wells.

GROUND WATER IN THE MODESTO AREA

This part of the report presents a brief summary of the occurrence and movement of ground water in the model area.

Occurrence of Ground Water

In the Modesto area, ground water occurs in an unconfined aquifer, in a confined aquifer, both of which are composed of unconsolidated materials, and in a consolidated-rock aquifer, where water is both perched and confined.

The unconfined aquifer occurs in unconsolidated deposits of Quaternary age overlying and extending east of an extensive confining bed, the so-called E-clay of Pleistocene age, which lies at depths ranging from about 130 ft (40 m) to 220 ft (67 m) (Hotchkiss, 1972, figs. 5 and 6; Page and Balding, 1973, fig. 6). Thus, the unconfined aquifer above the E-clay ranges in thickness from about 130 ft (40 m) to 220 ft (67 m). East of the E-clay (fig. 2), the base of the unconfined aquifer is at the top of the consolidated rocks, the Mehrten Formation of Miocene and Pliocene age. Depth to the top of the Mehrten ranges from zero in the eastern part of the area to over 900 ft (270 m) in the western part. East of the E-clay, the unconfined aquifer ranges in thickness from zero near the eastern part of the modeled area to about 900 ft (270 m) near the eastern edge of the E-clay beneath Modesto. Water levels in the unconfined aquifer range in depth from less than 10 ft (3 m) in the western part of the modeled area to about 90 ft (27 m) in the extreme eastern central part.

The confined aquifer occurs in the unconsolidated deposits of Tertiary and Quaternary age that underlie the E-clay. The base of the confined aquifer probably is at the top of the Mehrten. Only a few wells penetrate the confined aquifer beneath the E-clay, and data from them indicate that the head in the confined aquifer is less than that in the overlying unconfined aquifer (Page and Balding, 1973, fig. 17). The probable reason for that difference is that ground water is being pumped from beneath the E-clay west of the area (Hotchkiss and Balding, 1971, p. 38 and 61).

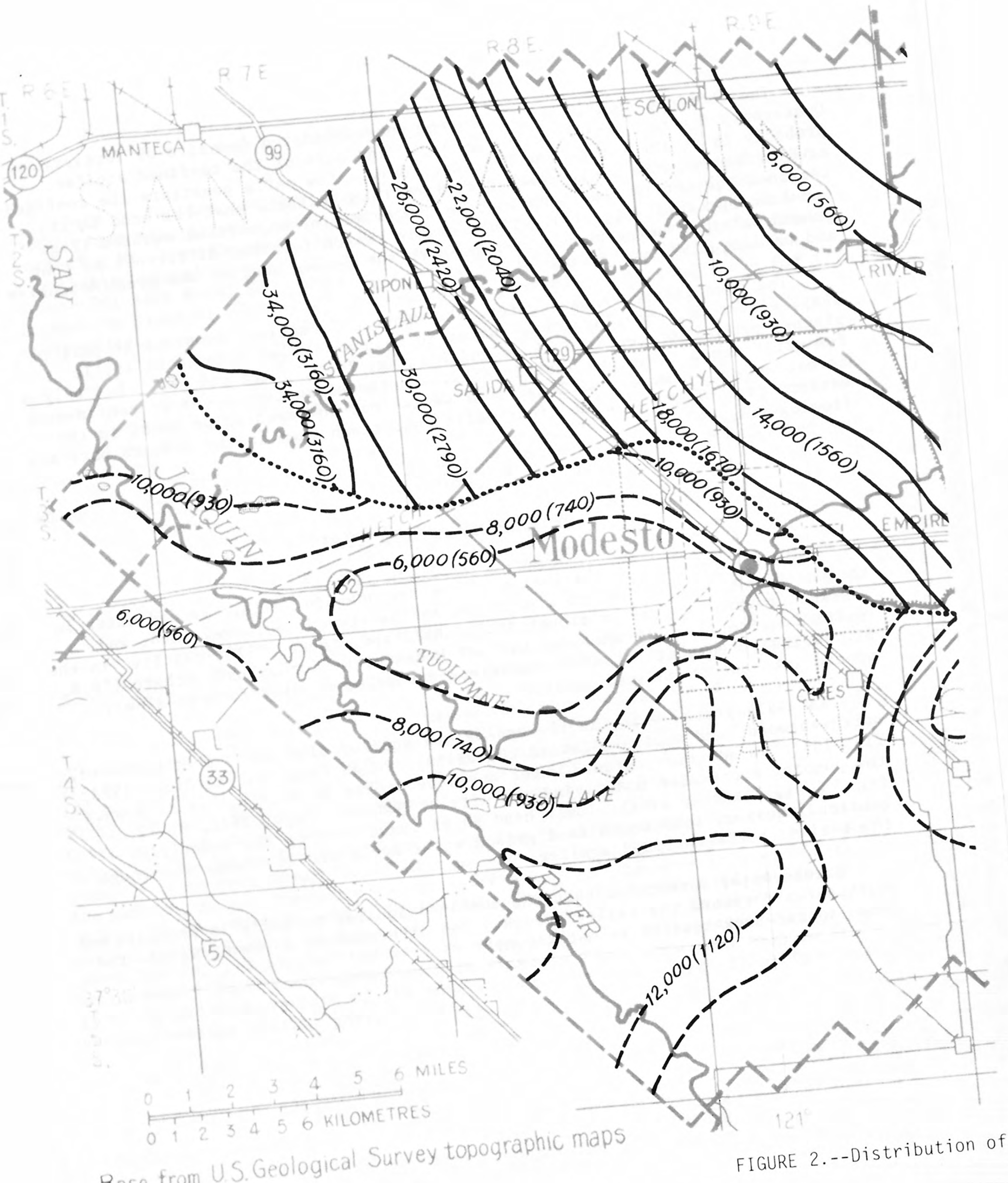
The consolidated-rock aquifer, the Mehrten Formation, consists in part of clay, siltstone, and claystone. Water in this and older formations is, in places, perched or confined (Page and Balding, 1973, p. 22 and 39). But only a few wells reach the consolidated rocks, and therefore the extent of confinement is not known. However, at least four wells that do reach those rocks in the eastern part of the area and four wells that reach them in the western part are flowing (fig. 4).

Movement of Ground Water

Before extensive pumping began in the San Joaquin Valley, ground water in the unconfined aquifer of the area moved southwestward, northwestward, and westward toward the valley trough (Mendenhall and others, 1916, pl. 1). In the confined aquifer beneath the area west of Modesto, Mendenhall and others (1916, pl. 1) indicated that artesian conditions caused some water to move slowly upward into the unconfined aquifer.

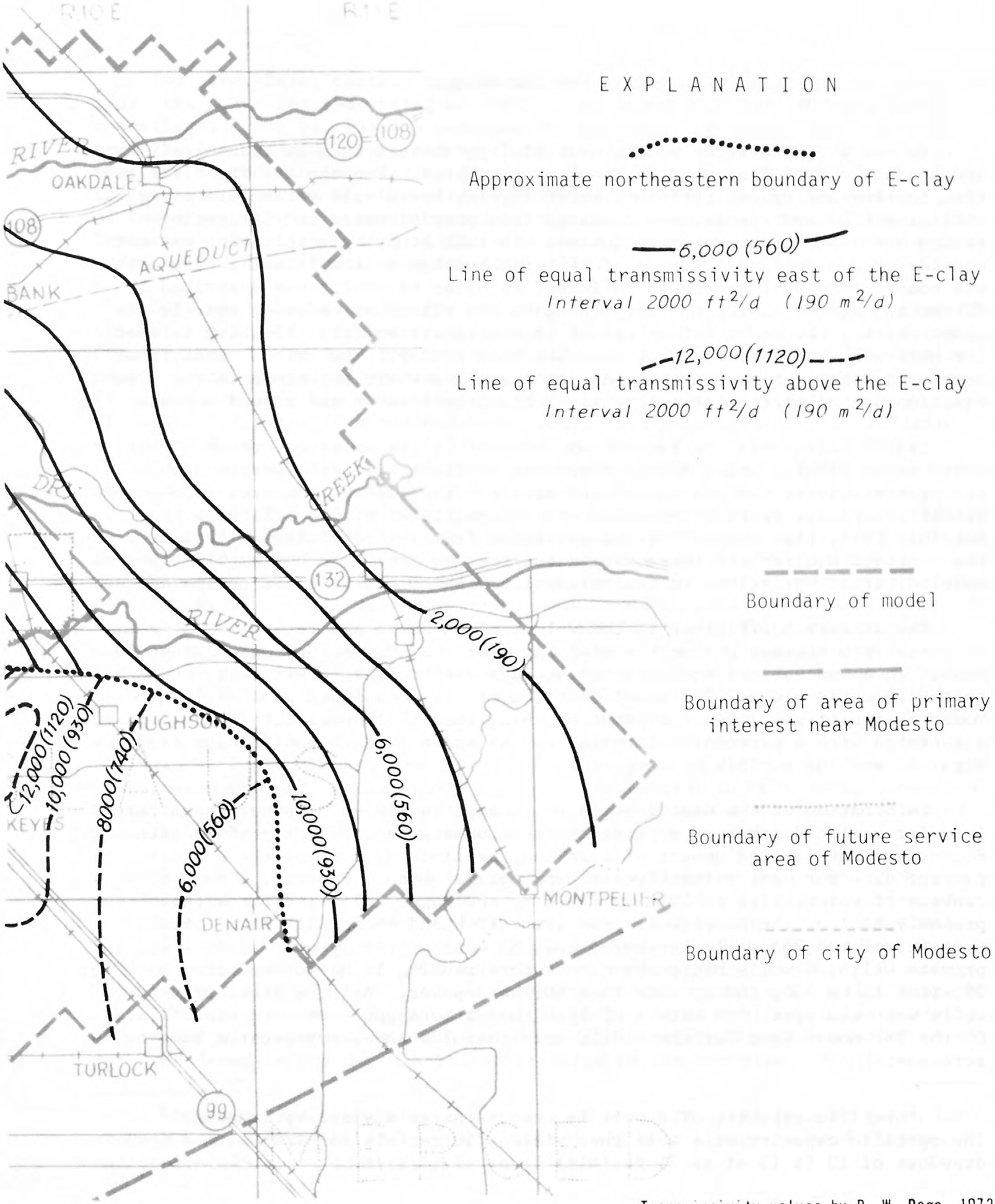
In 1971, ground water in the unconfined aquifer also moved southwestward, northwestward, and westward toward the valley trough (Page and Balding, 1973, fig. 14). In addition, ground water moved as it had in previous years toward the pumping depression underlying the city of Modesto (Page, 1972, p. 12, figs. 6-9). Because of the lower head in at least part of the underlying confined aquifer, some unconfined ground water moved slowly downward through the E-clay to the confined aquifer.

Ground-water movement within the confined aquifer probably is westward and southwestward toward the valley trough. The direction of movement within the consolidated-rock aquifer is not known.



Base from U.S. Geological Survey topographic maps

FIGURE 2.--Distribution of



Transmissivity values by R. W. Page, 1973

estimated transmissivity.

DATA FOR THE MODEL

To use a ground-water model, essential parameters such as transmissivity and storage coefficient must be known or estimated. Pumpage and its distribution in time and space, pertinent water levels, hydrologic parameters of any confining beds and rivers, and recharge from precipitation and irrigation return also must be known or estimated. In this study, precipitation was not considered a significant source of recharge because soil moisture in the area was considered to be generally deficient (similar to conditions described by Mitten and others, 1970, p. 22). The data are placed at nodes (a node is the point where a row and a column cross) in a grid system (fig. 1) which is used for entering data into the flow equation (see p. 20). The grid is made finer near areas where stress on the model is large and where solutions to the flow equation are of particular interest, such as the area in and around Modesto.

Transmissivity is the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. In the Modesto area, the transmissivity for the unconfined aquifer (fig. 2) was computed from specific capacity tests[1] (Thomasson and others, 1960, p. 220-222; Page and Balding, 1973, fig. 11, p. 28) and estimated from drillers' logs. Because the confined aquifer and the consolidated-rock aquifer were not explicitly modeled, areal variations in transmissivity within them were not estimated.

The storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an unconfined aquifer, the storage coefficient is virtually equal to the specific yield. The specific yield of the unconfined aquifer in the Modesto area (fig. 3) was estimated by using values of specific yield associated with a particular lithofacies, as shown by Page and Balding (1973, figs. 12 and 13, p. 29).

Information on the distribution of pumpage in time and space was gathered from irrigation districts, a private water company, and the city of Modesto. Because of the limited amount of time and the limited scope of the project, pumpage data for most private wells were not gathered. However, a selective canvass of water wells in 1970-71 (Balding and Page, 1971) indicates that probably most of the pumpage is from irrigation and municipal wells. For example, of the 253 wells canvassed only 85 were privately owned. Of the private wells, 4 wells had pumps with motors ranging in horsepower from 5 to 15; 28, from 15 to 100; and 2, more than 100 horsepower. All the other private wells were equipped with motors of less than 5 horsepower or with windmills. Of the 980 nodes used for the model, more than 220 nodes represented pumping stresses.

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[1] Specific capacity of a well is the discharge divided by drawdown. The specific capacity of a well that yields 750 gal/min (47 ℓ/s) with a drawdown of 10 ft (3 m) is 75 gal/min)/ft or 15 (ℓ/s)/m.

Two water-level contour maps were used in the study, one for the spring of 1952, the other for the spring of 1962 (figs. 4 and 5). The 1952 map (Davis and others, 1959, pl. 15) was modified by changing some water-level contours near the San Joaquin River, and by changing water-level contours in and near the city of Modesto in order to fit water-level data for city wells. Further, the map was modified by extrapolating water-level contours to the eastern part of the area. The 1962 map prepared by the California Department of Water Resources (unpublished data, 1962) also was modified by changing contours in order to fit water-level data for city wells.

Data were also gathered for the E-clay in the area. Those data included: (1) Thickness, which ranged from 20 ft (6 m) to 100 ft (30 m), as determined from drillers' logs and from Hotchkiss (1972, fig. 6); (2) vertical hydraulic conductivity (Davis and others, 1964, table 14) which averaged 4.2×10^{-9} ft/s (1.3×10^{-9} m/s) for six variable-head permeameter tests and 4.8×10^{-11} ft/s (1.5×10^{-11} m/s) for 16 one-dimensional consolidation tests, and (3) specific storage[2] (Riley, no date, p. 423-431) which ranged from about 4.0×10^{-6}/ft (1.2×10^{-6} /m) for elastic conditions to about 2.3×10^{-4} /ft (7.0×10^{-5} /m) for inelastic conditions. Johnson and others (1968, p. A26-A27) indicated that the conductivities determined from the consolidation tests should be considered as more reliable than those determined from the permeameter tests, and that to be meaningful, conductivities should be measured under field conditions. Consequently, the values used for vertical conductivities were from tests made by the U.S. Bureau of Reclamation (unpublished data, 1973) which determined an average conductivity of 4.12×10^{-11} ft/s (1.26×10^{-11} m/s) for three samples under a load of 200-400 lb/in^2 (1,380-2,860 kN/m^2) and a conductivity of 1.05×10^{-10} ft/s (3.20×10^{-11} m/s) for a sample under a load of 100-200 lb/in^2 (690-1,380 kN/m^2). Most computer runs in the model were made using the value of 1.05×10^{-10} ft/s (3.20×10^{-11} m/s) because that value was determined at a load which is closer to the load on the E-clay in the area than is 4.12×10^{-11} ft/s (1.26×10^{-11} m/s). The values of specific storage were determined for clays and silts below the E-clay near Pixley, Calif. However, D. C. Helm of the Geological Survey (oral commun., 1974) indicated that those values are representative of specific storage for most clays and silts in the San Joaquin Valley.

Data from a report by the Stanislaus County Planning Department (1957) were used to estimate recharge to the unconfined aquifer from percolation of irrigation water. Estimated surface water delivered to crops in the Modesto Irrigation District in 1956 was about 243,000 acre-ft (300 hm^3), and water used by crops was about 217,000 acre-ft (268 hm^3) (Stanislaus County Planning Department, 1957, p. 73-74). Thus, recharge to the unconfined aquifer beneath the district was about 26,000 acre-ft (31 hm^3). Water spilled during delivery and ground water pumped into canals and possibly returned to the aquifer were not considered in the calculation of recharge to the unconfined aquifer.

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[2] The specific storage is the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head (Lohman and others, 1972, p. 13).

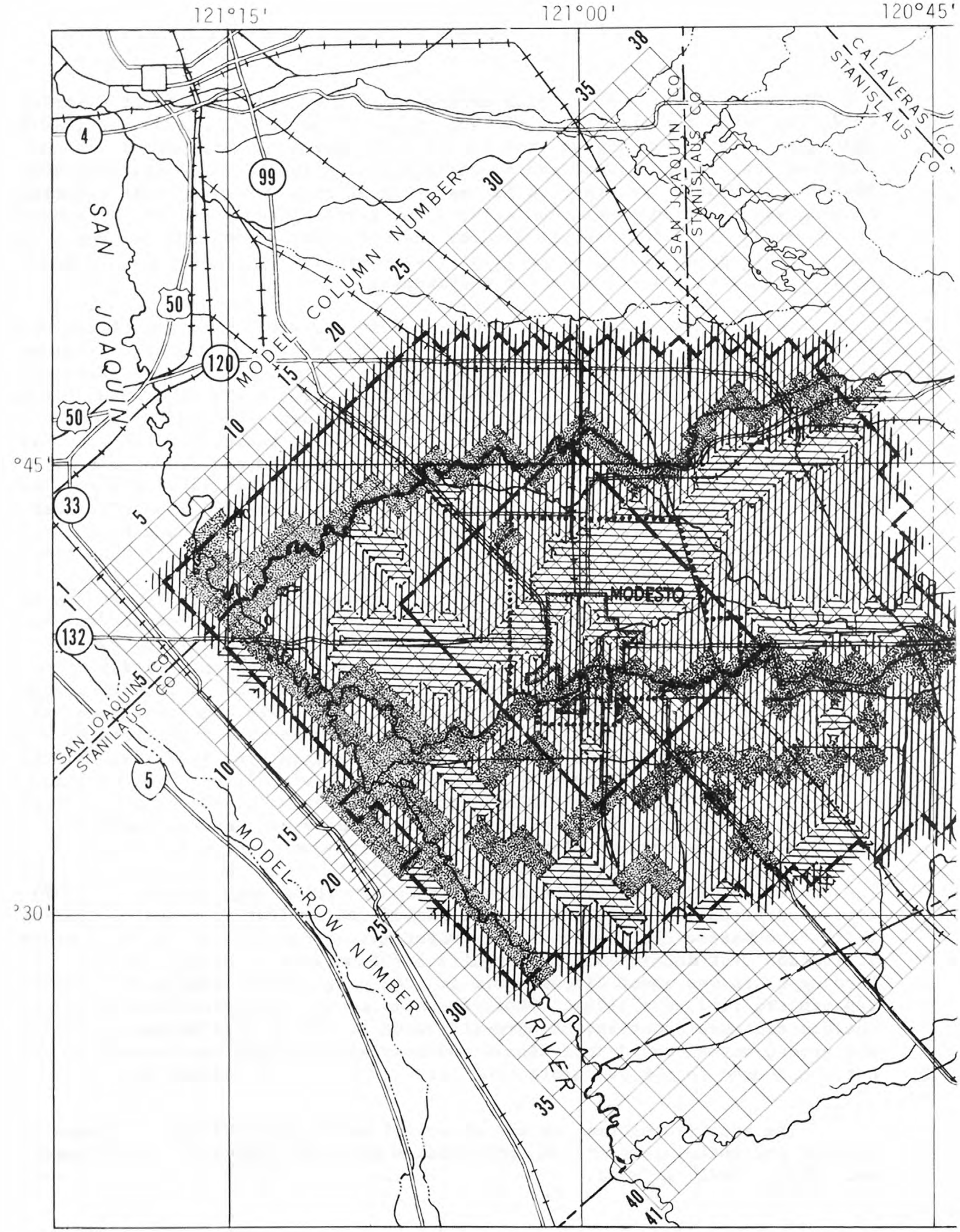
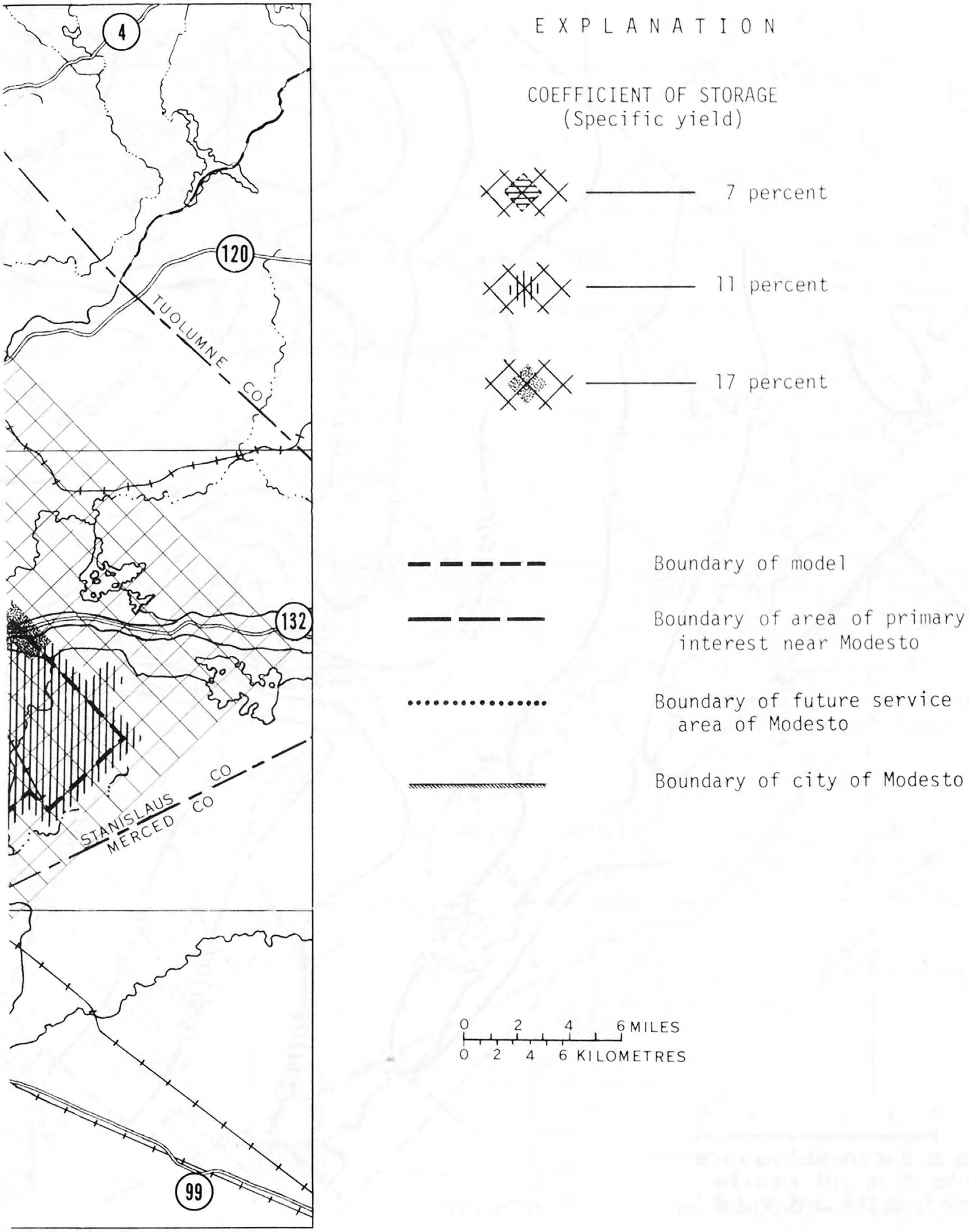
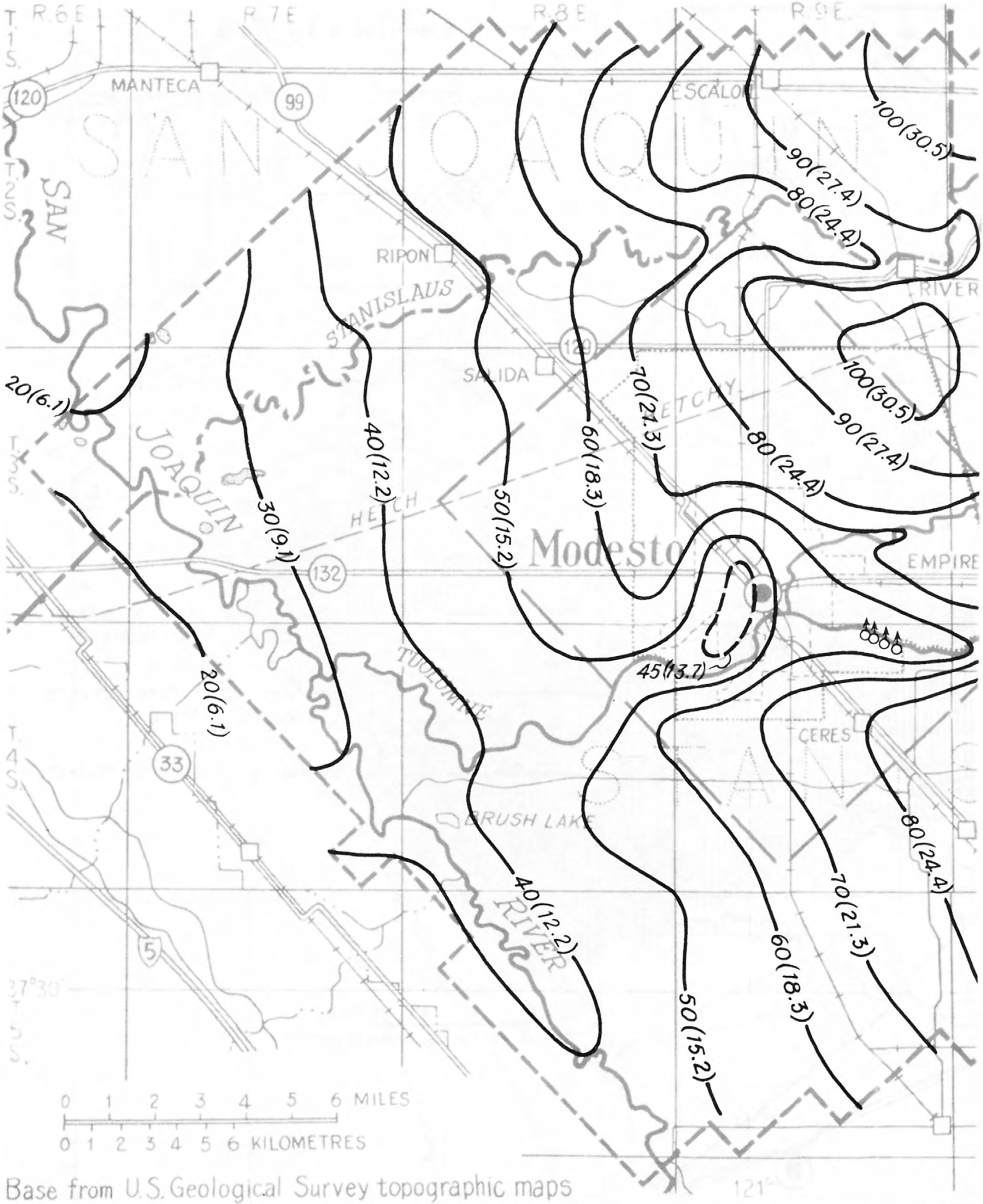


FIGURE 3.-- Distribution of

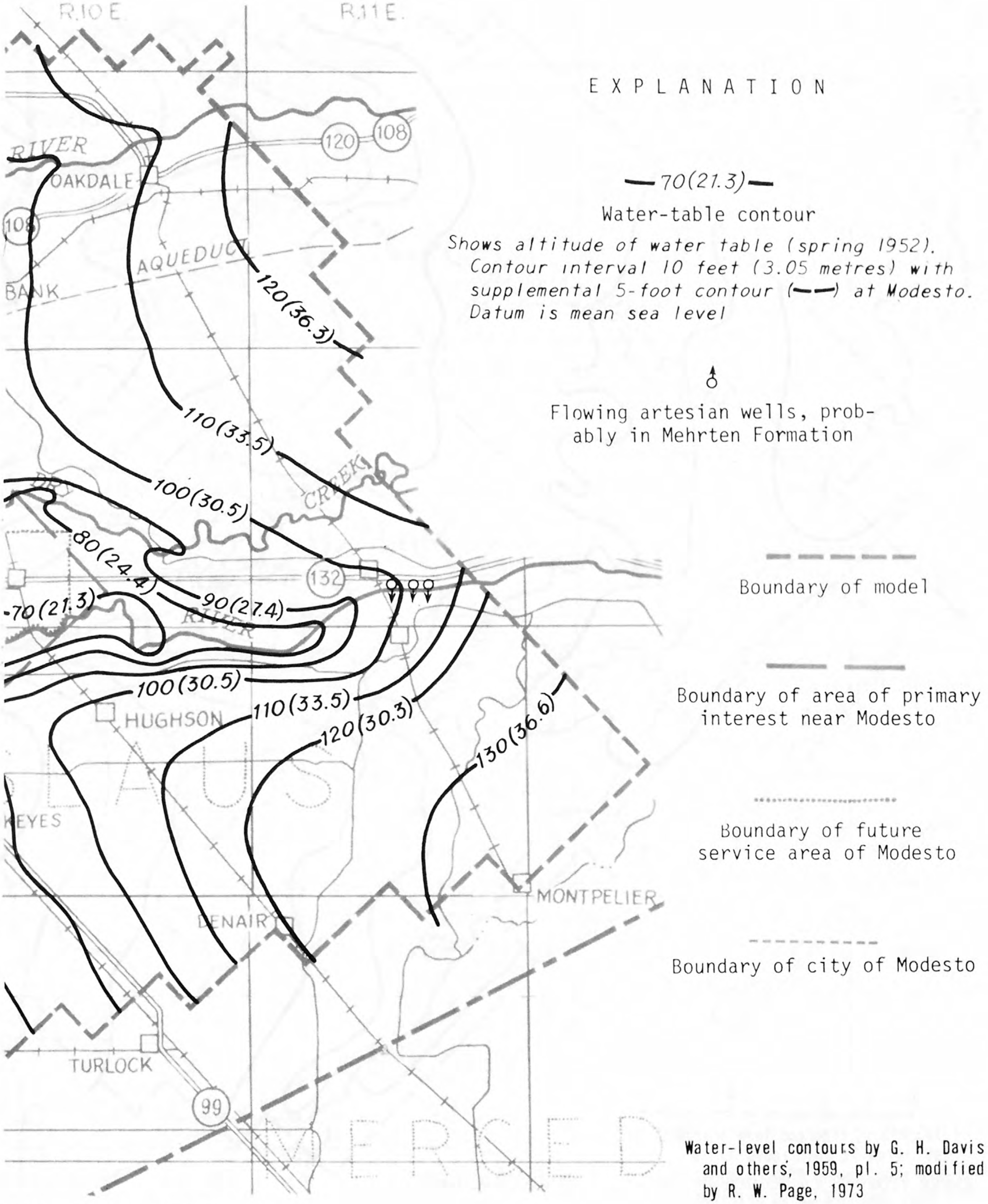


estimated specific yield.



Base from U.S. Geological Survey topographic maps

FIGURE 4.--Altitude of



EXPLANATION

—70(21.3)—

Water-table contour

Shows altitude of water table (spring 1952). Contour interval 10 feet (3.05 metres) with supplemental 5-foot contour (— —) at Modesto. Datum is mean sea level

Flowing artesian wells, probably in Mehrten Formation

Boundary of model

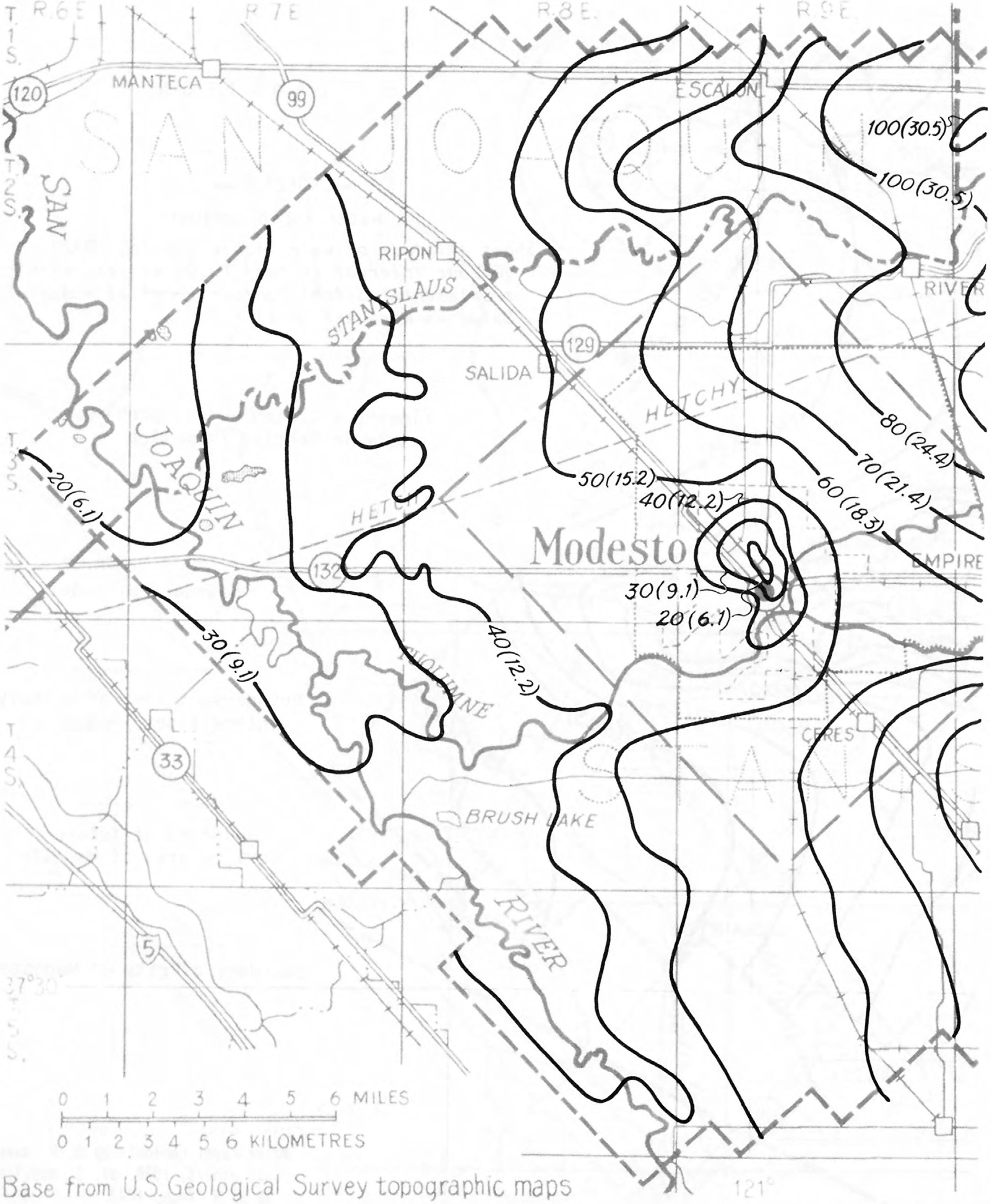
Boundary of area of primary interest near Modesto

Boundary of future service area of Modesto

Boundary of city of Modesto

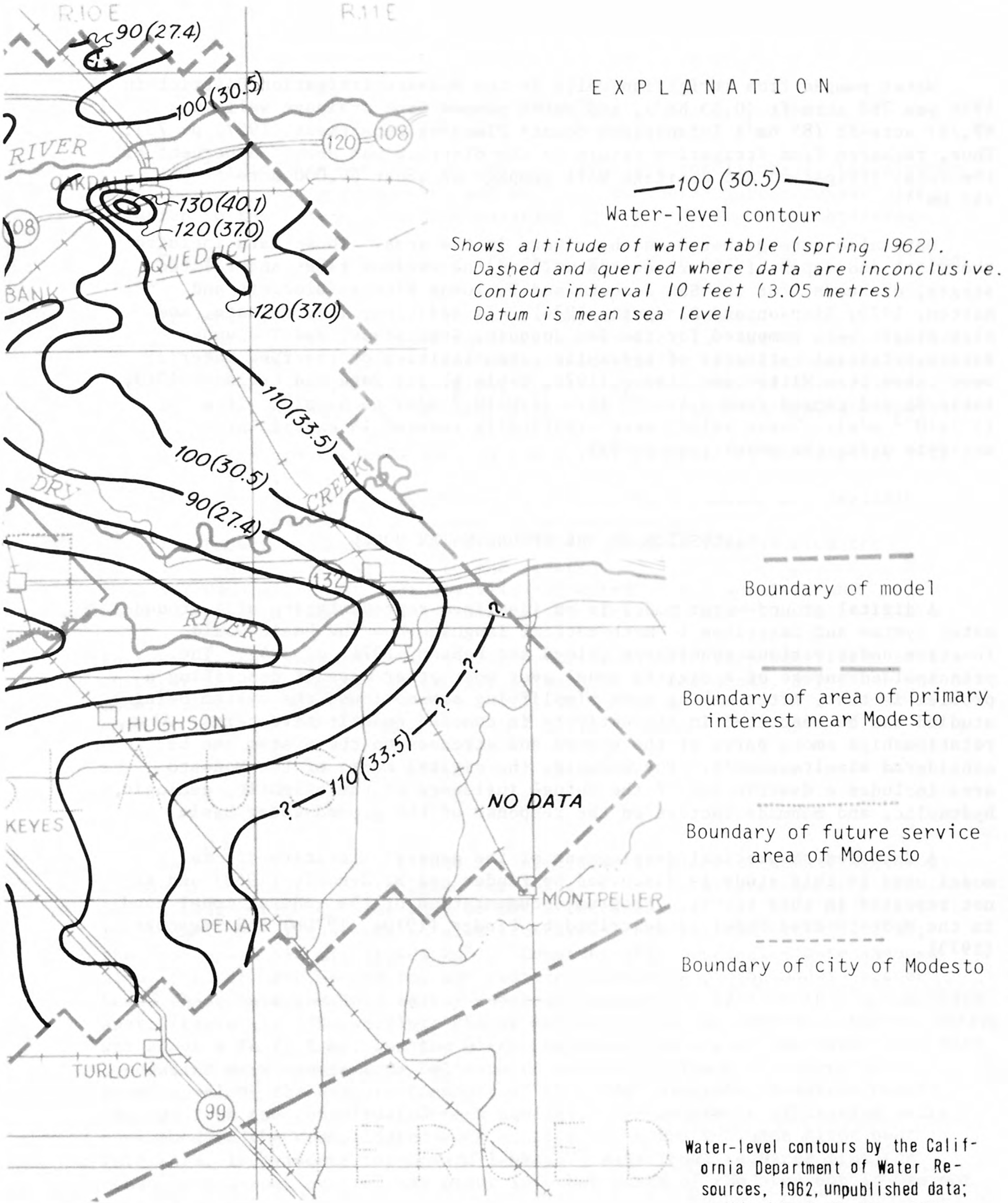
Water-level contours by G. H. Davis and others, 1959, pl. 5; modified by R. W. Page, 1973

water table, spring 1952.



Base from U.S. Geological Survey topographic maps

FIGURE 5.--Altitude of



Water-level contours by the California Department of Water Resources, 1962, unpublished data; modified by R. W. Page, 1973

water table, spring 1962.

Water pumped from irrigation wells in the Modesto Irrigation District in 1956 was 268 acre-ft (0.33 hm^3), and water pumped from drainage wells was 68,767 acre-ft (85 hm^3) (Stanislaus County Planning Department, 1957, p. 73). Thus, recharge from irrigation return in the district was about 38 percent of the total irrigation and drainage well pumpage of about 69,000 acre-ft (85 hm^3).

Data also were gathered on the rivers in the area. Those data included the width and depth of the rivers as well as the various flows and related stages, or heads, for the San Joaquin and Tuolumne Rivers (Blodgett and Mitten, 1970; Simpson and Blodgett, 1974). In addition, low, average, and high stages were computed for the San Joaquin, Stanislaus, and Tuolumne Rivers. Initial estimates of hydraulic conductivities of riverbed material were taken from Mitten and others (1970, table 6) and Page and LeBlanc (1969, table 8) and ranged from $3.4x10^{-3}$ ft/s ($1.0x10^{-3}$ m/s) to $5.7x10^{-3}$ ft/s ($1.7x10^{-3}$ m/s). These values were drastically reduced in experimental analysis using the model (see p. 32).

DISCUSSION OF THE GROUND-WATER MODEL

A digital ground-water model is an idealized representation of a ground-water system and describes in mathematical language how the basin would function under various conditions (Bloyd and Robson, 1971, p. 3-4). The principal advantage of a digital model over most other ways of describing a problem is that, after making some simplifying assumptions, the system being studied can be described in its entirety in concise quantitative terms. Also, relationships among parts of the system and stresses on the system can be considered simultaneously. For example, the digital model of the Modesto area includes a description of the mutual influence of the climatic, geologic, hydraulic, and manmade factors on the response of the ground-water basin.

A detailed theoretical development of the general iterative digital model used in this study is discussed by Pinder and Bredehoeft (1968) and is not repeated in this report. Program documentation of the general model used in the Modesto area model is described by Pinder (1970a, 1970b) and Trescott (1973).

Assumptions

Simplifying assumptions concerning hydrologic conditions in the ground-water basin in and near Modesto and of the flow therein are necessary if a solution to the generalized flow equation (see p. 20) is to be obtained.

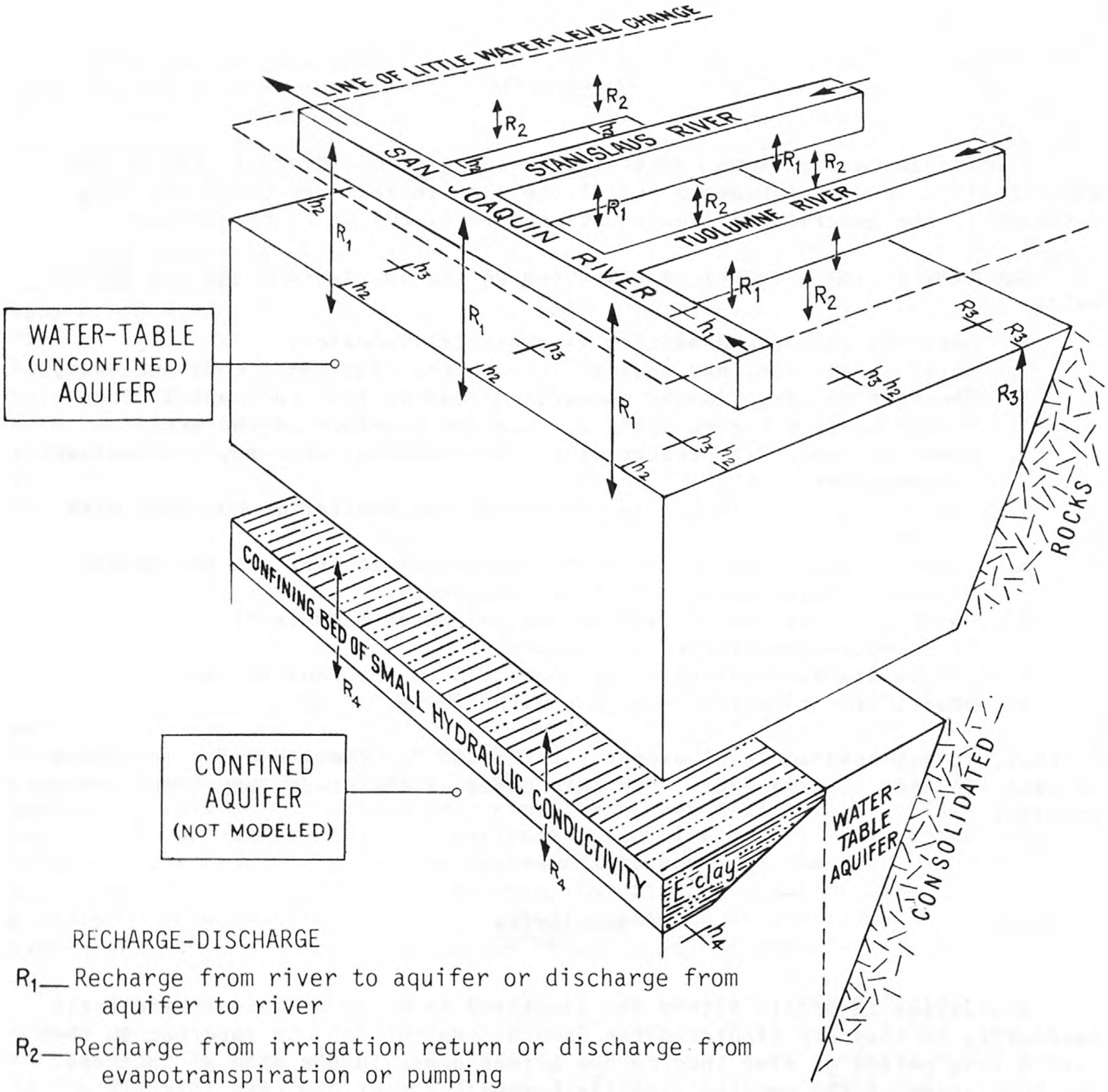
The simplifying assumptions are shown partly in figure 6 and are listed below:

1. Only the unconfined aquifer is explicitly modeled,
2. Water in the confined aquifer beneath the clay has a constant head,
3. Constant recharge to the unconfined aquifer from the consolidated-rock aquifer occurs along the eastern boundary of the area,
4. Constant heads are present along the northern, western, and southern boundaries,
5. The storage coefficient in the unconfined aquifer is constant with time,
6. Vertical flow components in the unconfined aquifer are negligible compared with horizontal flow components,
7. Under steady-state conditions, ground-water flow is from the unconfined aquifer to the rivers,
8. Canals are not hydraulically connected to the aquifer, and
9. Head in the rivers is constant with time.

Further, it was assumed that, except for floods, Dry Creek had little effect on water levels. Consequently, for this phase of the study, Dry Creek was not modeled.

Boundaries

Boundaries in models either are simulated in place of actual hydrologic boundaries or they are simulated far enough from the area of interest so that over a long period of time they do not affect heads in the area of interest. The boundaries of the modeled area lie beyond those of the city (fig. 1); they encompass 542 mi^2 (1,404 km^2). Constant-head boundaries were assumed along the northern, southern, and western boundaries of the model because heads there have remained fairly constant between two periods that are 10 years apart (table 1). The absolute change in head along the constant-head boundaries was about 4 ft (1.2 m), and the effect on model results of the assumption that boundaries were constant is believed to be small. The constant-recharge boundary along the eastern boundary of the model simulates possible upward leakage from the consolidated-rock aquifer. The existence of flowing wells, developed in the consolidated-rock aquifer along the Tuolumne River near Waterford, is evidence for upward leakage. Additional recharge from the consolidated-rock aquifer may occur in other parts of the area but it was not modeled at this time.



RECHARGE-DISCHARGE

R_1—Recharge from river to aquifer or discharge from aquifer to river

R_2—Recharge from irrigation return or discharge from evapotranspiration or pumping

R_3—Constant recharge along eastern boundary

R_4—Recharge from confined aquifer to unconfined or discharge from unconfined to confined

HEADS

h_1—Head in river at a given node

h_2—Constant head at a given node along northern, western, and southern boundaries

h_3—Head generated by model at a given node

h_4—Head of confined aquifer at a given node, remains constant

FIGURE 6.--Conceptual model of the hydrologic system in and near Modesto.

Table 1.--*Net change in head along model constant-head boundaries, spring 1952 to spring 1962*

Row	Column	Net change (ft)	Row	Column	Net change (ft)	Row	Column	Net change (ft)
3	5	-5	7	4	-1	32	6	-2
3	6	-5	7	28	-19	32	7	-2
3	7	-5	8	4	0	33	7	-2
3	8	-6	8	29	-21	33	8	-2
3	9	-6	9	4	+1	33	10	-2
3	10	-3	10	4	+1	34	10	-1
3	11	-3	11	4	0	34	11	-3
3	12	-2	12	4	0	34	12	-2
3	13	-2	13	4	-1	34	13	-2
3	14	-2	14	4	-2	35	13	0
3	15	-2	15	4	-2	35	14	-1
3	16	-3	16	3	-4	35	15	-3
3	17	-4	17	3	-3	35	16	-4
3	18	-5	18	3	-2	35	17	-4
3	19	-7	19	4	-2	36	17	-4
3	20	-7	20	4	-1	36	18	-4
3	21	-7	21	4	-1	36	19	-4
3	22	-7	22	4	-2	36	20	-2
3	23	-9	23	3	-2	36	21	-4
3	24	-9	24	3	-2	36	22	-6
4	4	-5	25	3	0	37	22	(1)
4	24	-10	26	3	+2	37	23	(1)
4	25	-10	27	3	+3	37	24	(1)
5	4	-1	28	3	+2	37	25	(1)
5	25	-16	29	3	+1	38	25	(1)
5	26	-15	30	3	0	38	26	(1)
6	4	0	31	3	0	38	27	(1)
6	27	-18	32	5	-4	39	27	(1)

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[1] No data for 1962.

In the model, a constant-head boundary was simulated about 10 mi (16 km) west of the center of Modesto; it is the closest boundary to the geographic center of the city. Analytical solutions indicated that the boundary would not have much effect on the drawdown of a well being pumped near the center of the city. For example, near the center of the city, it would affect the drawdown of a well by less than 0.0001 ft (0.00003 m) after 10 years of pumping, where discharge from the well is 2,000 gal/min (130 ℓ/s), transmissivity is 8,000 ft^2/d (70 m^2/d), and the coefficient of storage is 0.10. Pumping the same well for 10 years in an infinite aquifer would cause a drawdown of about 0.1 ft (0.03 m) at a radius of 10 mi (16 km) from the well. If a similar well were being pumped very near a constant-head boundary, the effect of the boundary at a distance of 10 mi (16 km) after 10 years of pumping would be to cancel the drawdown caused by the well.

Nevertheless, if heads do not remain fairly constant along the boundaries and further testing of the model indicates that boundaries are influencing heads in city wells, then the boundaries may have to be simulated farther north, south, and west so that they will have negligible effect on solutions for head in the unconfined aquifer beneath the city.

Methods of Study

After the initial values of transmissivity and storage had been estimated, a 1952 water-level contour map was chosen to represent steady-state conditions (see page 22). The reasonableness of the head configuration of this map and of the estimated values of transmissivity were tested using a program described below.

The continuous form of the two-dimensional differential equation used to describe the flow conditions in the nonhomogeneous, anisotropic, unconfined aquifer of the Modesto area is:

$$\partial/\partial x\ (T_{xx}\partial h/\partial x) + \partial/\partial y\ (T_{yy}\partial h/\partial y) = S\frac{\partial h}{\partial t} + W \qquad (1)$$

where x,y are orthogonal coordinate directions (L),

T_{xx} is transmissivity in the x direction (L^2T^{-1}),

T_{yy} is transmissivity in the y direction (L^2T^{-1}),

h is the hydraulic head (L),

S is the storage coefficient (dimensionless),

W is the net rate of recharge-discharge per unit area (LT^{-1}) (net flux), and

t is time (T).

The model is used to solve a discrete form of equation 1 for head at all nodes at the end of discrete time steps where values of T, S, and W are known. W is a difficult parameter to estimate. However, if values of T and h are known, then under steady-state conditions, the time derivitive equals zero, and the value for W can be found by using the remaining terms of the equation. Thus, under steady-state conditions the form of the equation is:

$$\partial/\partial x\ (T_{xx}\partial h/\partial x) + \partial/\partial y\ (T_{yy}\partial h/\partial y) = W \qquad (2)$$

Substituting estimated values of T and h into the discrete form of this equation, a computer program is used to compute a solution for W (net flux) at each node in the model.

Plotting the proper sign (+ or -) of W, yields a map that indicates areas of recharge or discharge. Also the values of W can be compared, and any value of W that is considerably different from surrounding values is easily noticed. Values of W that are considerably different and obviously unreasonable can be adjusted by modifying T or h. The modified values of T and h are placed in the program and a computer run that computes a new value for W is made. This process is continued until a set of values for T, h, and W is generated wherein the values for T and h do not yield values of W that are judged to be unreasonably large or small. Also, adjusted values of T or h are checked for consistency with adjacent values of T or h.

The next step in a model analysis generally involves determining differences in all recharge and discharge from the time of assumed steady-state conditions until the present. These values are used to stress the model in discrete time steps so that the model will solve for h. This method of analysis assumes that all recharge and discharge are known from the time of steady-state conditions to the present. This assumption was not met in the Modesto area, because such data either were not readily available or were not available at all. Consequently, the 1952-62 period was chosen for testing because most of the pertinent data were available. Also, before 1952, steady-state conditions were approximated.

Prior to 1952, static water levels in and near Modesto were fairly constant (Page, 1972, fig. 10; Page and Balding, 1973, fig. 16; Page and others, 1974). Pumping of city wells, however, did cause as much as 25 ft (7.6 m) difference between static water levels and pumping levels. Nevertheless, in the spring of 1952 static water levels were at altitudes that were comparable to those of previous years.

Assuming nearly steady-state conditions for the spring of 1952, the values of heads from the modified spring 1952 map of Davis and others (1959, p. 15) (fig. 4) and the initial estimates of *T* were entered into the net-flux program, and an array of *W* values for spring 1952 was computed. By using this program, *T*, *h*, and *W* were adjusted until a reasonably consistent set of values for those parameters was generated--adjustment of *T* generally was less than 20 percent; adjustment of *h* generally was less than 5 ft (1.5 m). Next, the generated values of *T*, *h*, and *W*, together with the values of specific yield, were used in the Trescott model (1973) where a steady-state solution was reached within a simulated time of 0.03 year or about 10 days. Therefore, as far as the model was concerned, the conditions for steady state had been met.

Testing the parameters of the model from spring 1952 to spring 1962 required computing pumpages to stress the model and choosing subperiods over which that stress would be applied. To determine time periods over which pumpage could be considered constant, regression curves were fitted to volumes of water pumped from city of Modesto wells and Modesto Irrigation District wells (fig. 7). Irrigation pumpage, which is not shown in figure 7, did not show any trend. However, both drainage-well pumpage and city pumpage did show trends with time. Using these curves as a guide, two subperiods were selected to be stressed: spring 1952 to spring 1957, and spring 1957 to spring 1962. For the city, the 1955 pumpage was selected as the stress to be used in the first period, and the 1959 pumpage, as the stress to be used in the second period. For the area outside the city, the compiled pumpage of 1955 was selected as the stress to be used in the first period, and the compiled pumpage of 1958, as the stress to be used in the second period. The selection of the 1955 and the 1958 area pumpage was based on the curves for the drainage-well pumpage. The model was then ready to be tested over two successive 5-year periods using the selected stresses and various other hydrologic parameters.

SENSITIVITY ANALYSES

Sensitivity analyses consisted of determining model response when varying the magnitude of the model parameters by an amount proportional to the degree of uncertainty present in their determination. The degree of uncertainty can be determined statistically for some parameters and estimated for others. For this model, the degree of uncertainty associated with the various parameters was estimated.

Sensitivity testing consisted of varying a given parameter in the model and recording the changes in simulated head as a result of the change in the parameter. During a test, all other parameters were held constant at their initial values, except for the tests on irrigation return where transmissivity was increased by one and one-half times. The model was considered to be insensitive to a parameter if a small change in computed head [<1 ft (0.3 m)] resulted from changing a given parameter a given amount.

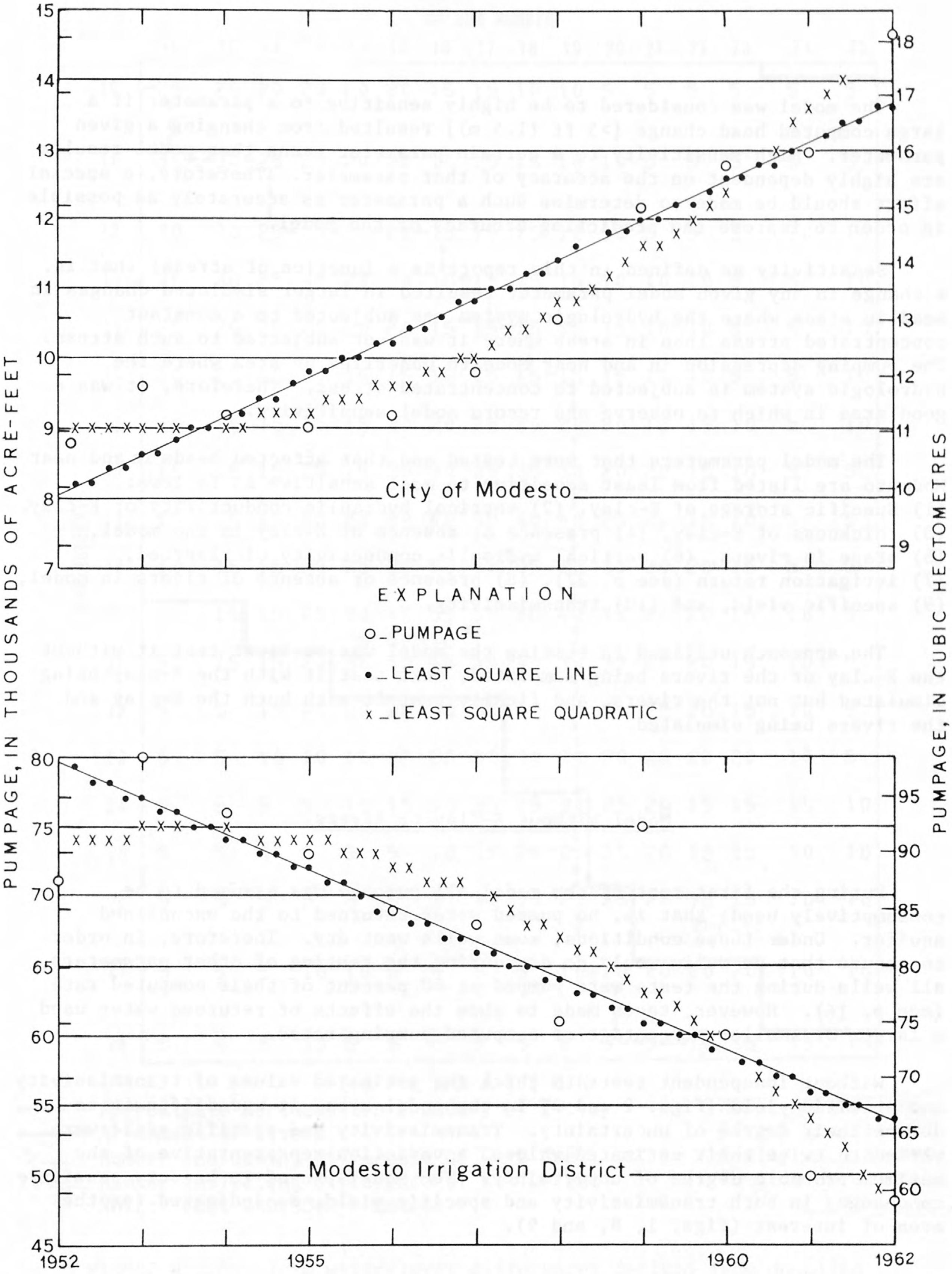


FIGURE 7.--Regression curves comparing pumpage of city of Modesto wells and Modesto Irrigation District drainage wells.

The model was considered to be highly sensitive to a parameter if a large computed head change [>5 ft (1.5 m)] resulted from changing a given parameter. High sensitivity to a certain parameter means that model results are highly dependent on the accuracy of that parameter. Therefore, a special effort should be made to determine such a parameter as accurately as possible in order to improve the predicting accuracy of the model.

Sensitivity as defined in this report is a function of stress; that is, a change in any given model parameter resulted in larger simulated changes in head in areas where the hydrologic system was subjected to a constant concentrated stress than in areas where it was not subjected to such stress. The pumping depression in and near Modesto underlies an area where the hydrologic system is subjected to concentrated stress. Therefore, it was a good area in which to observe and record model sensitivity.

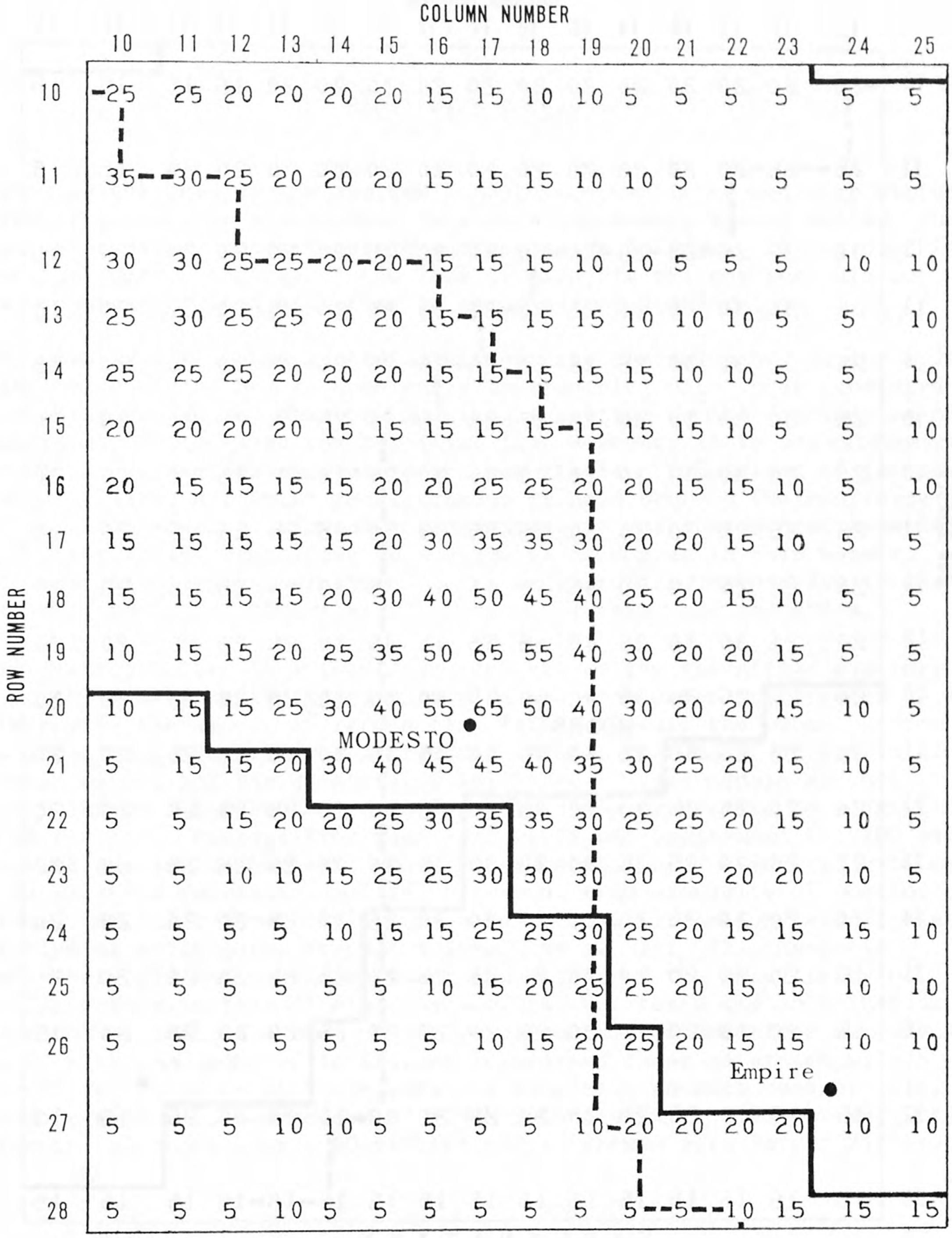
The model parameters that were tested and that affected heads in and near Modesto are listed from least sensitive to most sensitive as follows:
(1) Specific storage of E-clay, (2) vertical hydraulic conductivity of E-clay,
(3) thickness of E-clay, (4) presence or absence of E-clay in the model,
(5) stage in rivers, (6) vertical hydraulic conductivity of riverbed,
(7) irrigation return (see p. 27), (8) presence or absence of rivers in model,
(9) specific yield, and (10) transmissivity.

The approach utilized in testing the model was to first test it without the E-clay or the rivers being simulated, next test it with the E-clay being simulated but not the rivers, and finally test it with both the E-clay and the rivers being simulated.

Model Without E-Clay or Rivers

During the first test of the model all pumpage was assumed to be consumptively used; that is, no pumped water returned to the unconfined aquifer. Under those conditions, some wells went dry. Therefore, in order to ensure that no wells would go dry during the testing of other parameters, all wells during the tests were pumped at 60 percent of their computed rate (see p. 16). However, tests made to show the effects of returned water used a larger or smaller percentage of computed pumping rates.

Without independent tests to check the estimated values of transmissivity and specific yield (figs. 2 and 3) in the model area, it was difficult to define their degree of uncertainty. Transmissivity and specific yield were varied to twice their estimated values, a variation representative of the maximum probable degree of uncertainty. The model proved to be very sensitive to changes in both transmissivity and specific yield, as indicated for the area of interest (figs. 1, 8, and 9).



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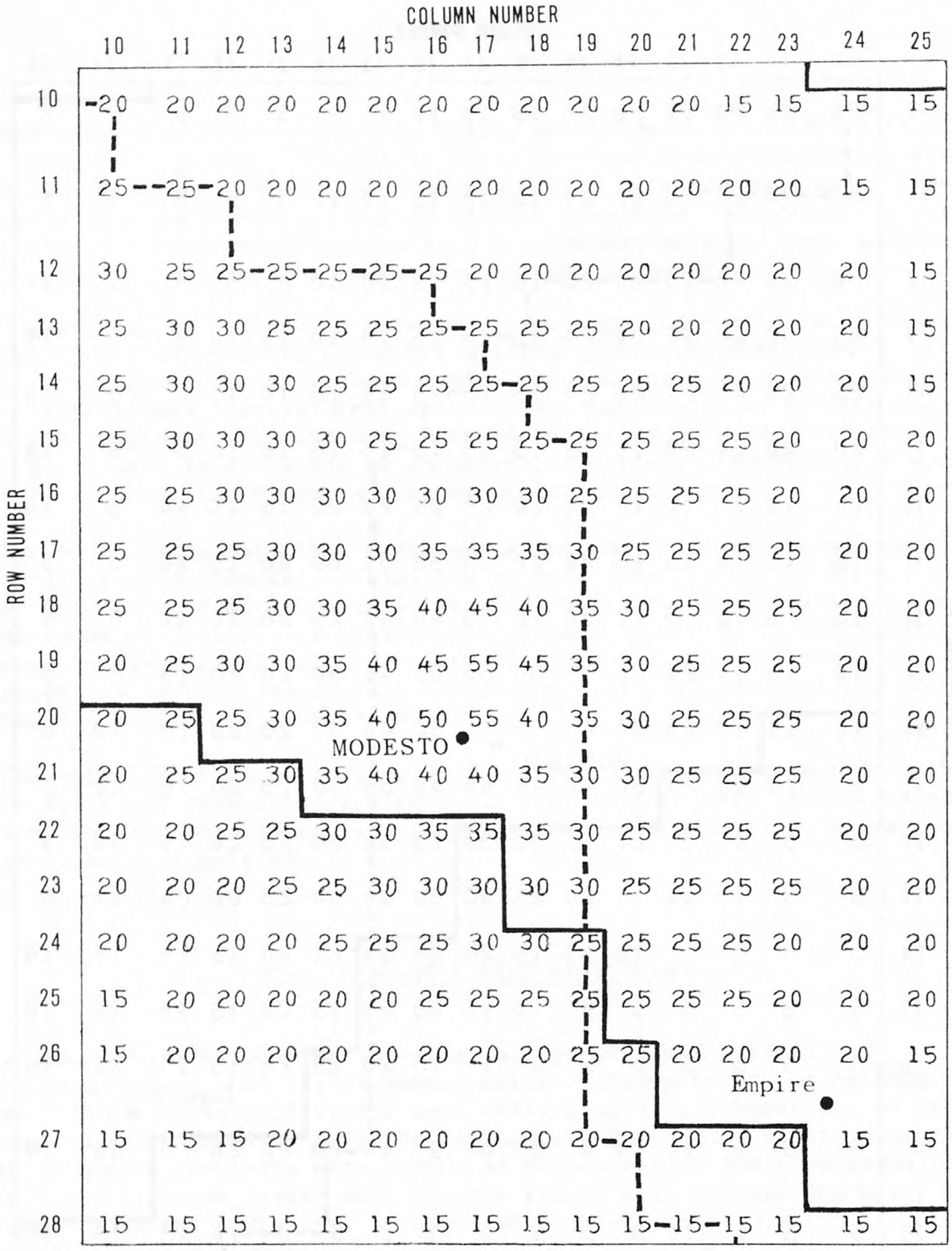
28	5	5	5	10	5	5	5	5	5	5	5	5	10	15	15	15

EXPLANATION

- - - - Approximate northeastern boundary of E-clay
——— Alinement of rivers
5___ Number indicating difference of 0-<5 feet
10___ Number indicating difference of 5-<10 feet
NOTE: Feet x 0.3048 = metres

MODEL ASSUMPTIONS
Rivers _____ absent
E-clay _____ absent
Pumping duration __
___ 10 years

FIGURE 8.--Absolute water-level differences derived from doubling estimated transmissivity.



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28	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15

EXPLANATION

- - - - Approximate northeastern boundary of E-clay
——— Alinement of rivers
5 ___ Number indicating difference of 0-<5 feet
10___ Number indicating difference of 5-<10 feet
NOTE: Feet x 0.3048 = metres

MODEL ASSUMPTIONS
Rivers _____absent
E-clay _____absent
Pumping duration__
____10 years

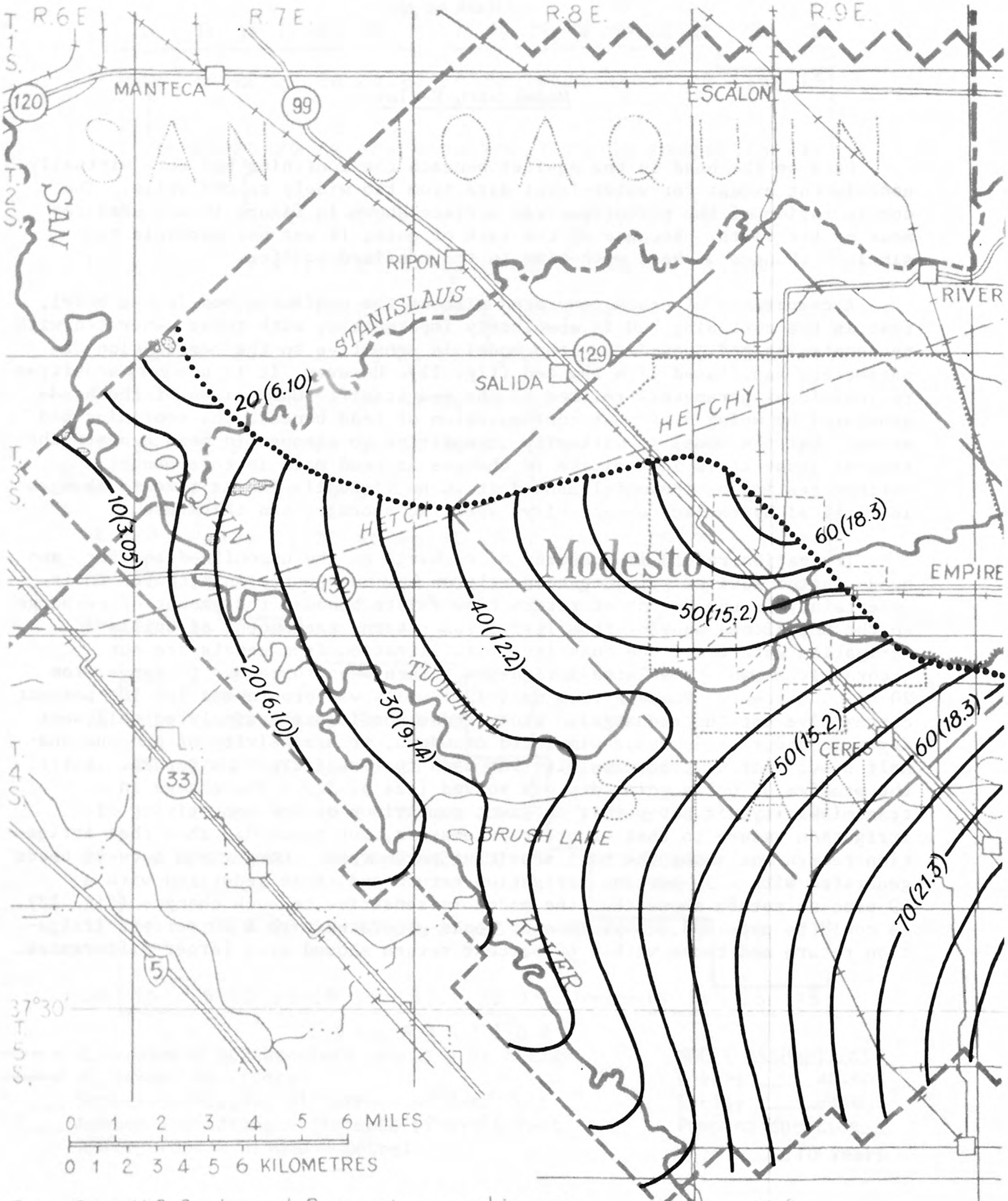
FIGURE 9.--Absolute water-level differences derived from doubling estimated specific yield.

Model With E-Clay

Data on the head in the aquifer beneath the confining bed were virtually nonexistent except for water-level data from two widely spaced wells. The configuration of the potentiometric surface shown in figure 10 was used for most of the tests. Because of the lack of data, it was not possible to simulate changes of head with time in the confined aquifer.

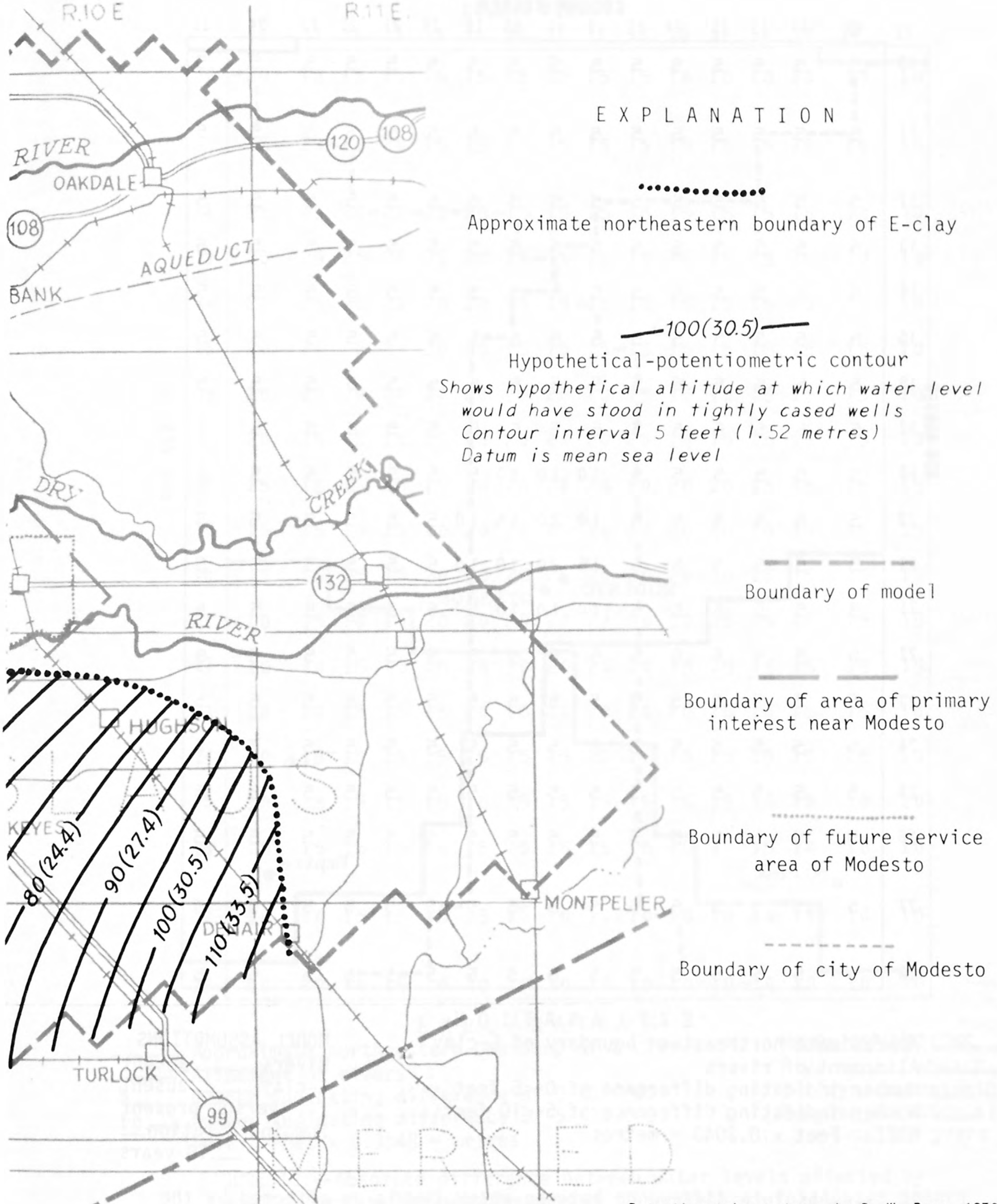
A comparison of heads generated without the confining bed in the model, that is the confining bed is absolutely impermeable, with those generated with the confining bed showed that the model is sensitive to the combination of parameters associated with the bed (fig. 11). However, it is not very sensitive to individual parameters related to the bed itself. Comparison of the heads generated by using different configuration of head beneath the confining bed showed that the model is virtually insensitive to changes in head beneath the bed--at least it is insensitive to changes in head made in this manner. Further testing of the model showed it to be virtually insensitive to changes in vertical hydraulic conductivity, specific storage, and thickness.

Irrigation return is a source of recharge to the unconfined aquifer, and heads in the aquifer will depend partly on how much water infiltrates to it. Uncertainty in the amount of return flow exists because the amount of recharge to the unconfined aquifer from irrigation return, the amount of spills of irrigation water, and the quantity of infiltration from canals are not accurately known. Simulated irrigation return was programmed to range from 20 to 60 percent. Pumpage from municipal wells was programmed for 100 percent consumptive use (no recharge). Under those conditions a simulated well went dry. In order to decrease simulated drawdown, transmissivity of one and one-half times initial transmissivity was used to test irrigation return. Later, the problem of wells going dry was solved (see p. 32). The change in transmissivity did not permit an exact comparison of the sensitivity of irrigation return to that of other parameters, but tests did show that irrigation return was among the most sensitive parameters. Comparison between heads generated with a 20 percent irrigation return and those generated with a 40 percent return shows that the model is sensitive to such changes (fig. 12). As could be expected, comparison of heads generated with a 20 percent irrigation return and those with a 60 percent return showed even larger differences.



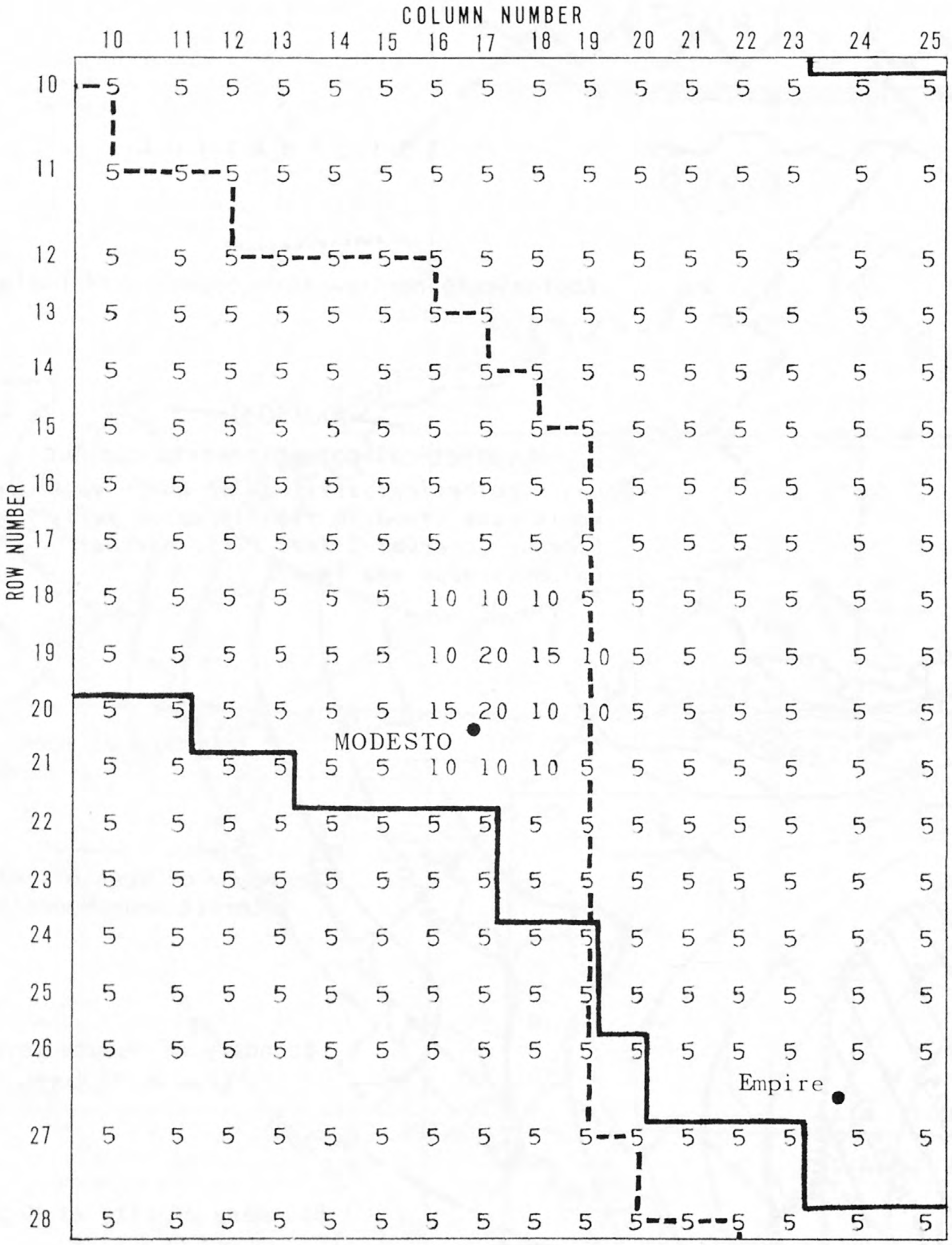
Base from U.S. Geological Survey topographic maps

FIGURE 10.--Hypothetical altitude of potentiometric surface of confined



Potentiometric contours by R. W. Page, 1973

water body beneath the E-clay in western part of Modesto area.



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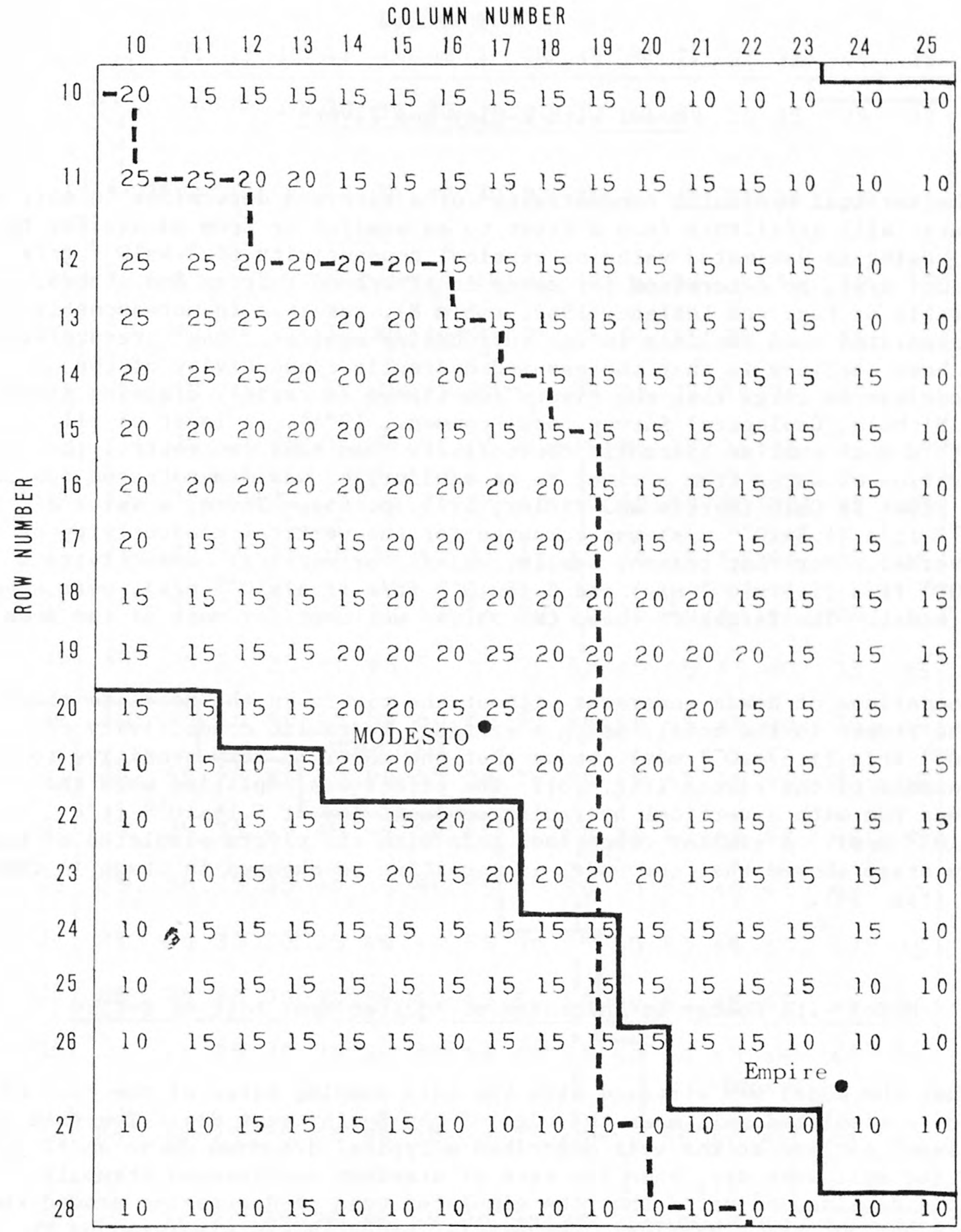
28	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5

EXPLANATION

----	Approximate northeastern boundary of E-clay
——	Alinement of rivers
5 ___	Number indicating difference of 0-<5 feet
10 ___	Number indicating difference of 5-<10 feet
	NOTE: Feet x 0.3048 = metres

MODEL ASSUMPTIONS
Rivers _____ absent
E-clay _____ absent versus present
Pumping duration _____ 10 years

FIGURE 11.--Absolute difference between water levels as affected by the presence or absence of the E-clay in the model.



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28	10	10	10	15	10	10	10	10	10	10	10	10	10	10	10	10

EXPLANATION

- - - - Approximate northeastern boundary of E-clay
——— Alinement of rivers
5___ Number indicating difference of 0-<5 feet
10___ Number indicating difference of 5-<10 feet
NOTE: Feet x 0.3048 = metres

MODEL ASSUMPTIONS
Rivers____absent
E-clay____present
Pumping duration_
____10 years

FIGURE 12.--Absolute difference between water levels affected by agricultural wells being pumped at 80 percent of full value and those being pumped at 60 percent.

Model With E-Clay and Rivers

The vertical hydraulic conductivity[3] of a riverbed determines in part how much water will infiltrate from a river to an aquifer or from an aquifer to a river. Using an estimated value of vertical conductivity of 3.4×10^{-3} ft/s (1.04×10^{-3} m/s), as determined for sands in riverbeds (Mitten and others, 1970, table 6; Page and LeBlanc, 1969, table 8), resulted in unreasonably large simulated head declines in the surrounding aquifer. One interpretation of the head declines is that the assumed hydraulic conductivity of the riverbeds was so large that the rivers functioned as rapidly draining sinks (W. D. Nichols, Geological Survey, oral commun., 1974). A layer of silt or mud with a much smaller hydraulic conductivity than sand can control the infiltration of water from a river to an aquifer, as was demonstrated for the Scioto River in Ohio (Norris and Fidler, 1969, p. 45). There, a value of 4.2×10^{-5} ft/s (1.3×10^{-5} m/s) was computed for the vertical conductivity of the riverbed. For that reason, smaller values for vertical conductivity, 5.16×10^{-4} ft/s (1.57×10^{-4} m/s) and 5.16×10^{-6} ft/s (1.57×10^{-6} m/s), were used in the model. The larger of these two values was used for most of the model runs.

Comparison of heads generated without the rivers in the model to those with the rivers in the model, using a vertical hydraulic conductivity of 5.16×10^{-4} ft/s (1.57×10^{-4} m/s), shows that the model is very sensitive to the presence of the rivers (fig. 13). The effect was amplified when the model was run with a vertical hydraulic conductivity of 5.16×10^{-6} ft/s (1.57×10^{-6} m/s). A similar comparison made with the rivers simulated at high and low stage showed that the model is sensitive to changes in stage in the rivers (fig. 14).

Model With Change in Thickness of Aquifer Near Edge of E-Clay

When the model was stressed with the 1973 pumping rates of the city of Modesto, a simulated well near the edge of the E-clay went dry. The rate of water-level decline at the well described a typical drawdown curve until just before the well went dry, when the rate of drawdown accelerated abruptly. The rapid decline indicated that the simulated cone of depression around the well had encountered a barrier. The barrier probably was simulated by the abrupt change in aquifer thickness near the edge of the confining bed, the E-clay (fig. 6). Because that change in thickness does not actually represent a barrier to ground-water flow, the abrupt change in thickness near the edge of the clay was modified to a gradual change in thickness. After this modification was made, none of the wells in the model went dry during a programmed simulation period of 20 years.

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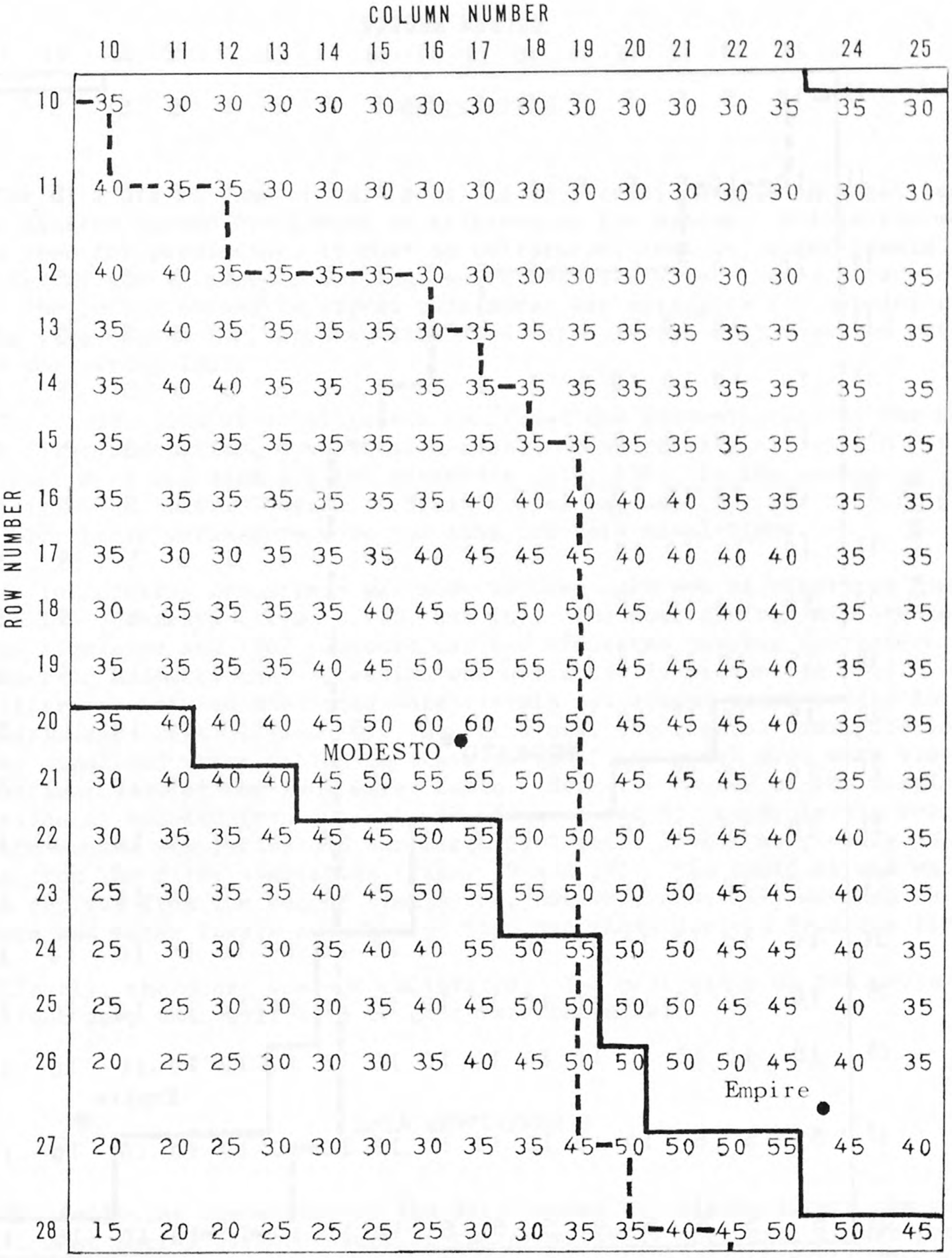
[3] The hydraulic conductivity of a medium is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (Lohman and others, 1972, p. 4).



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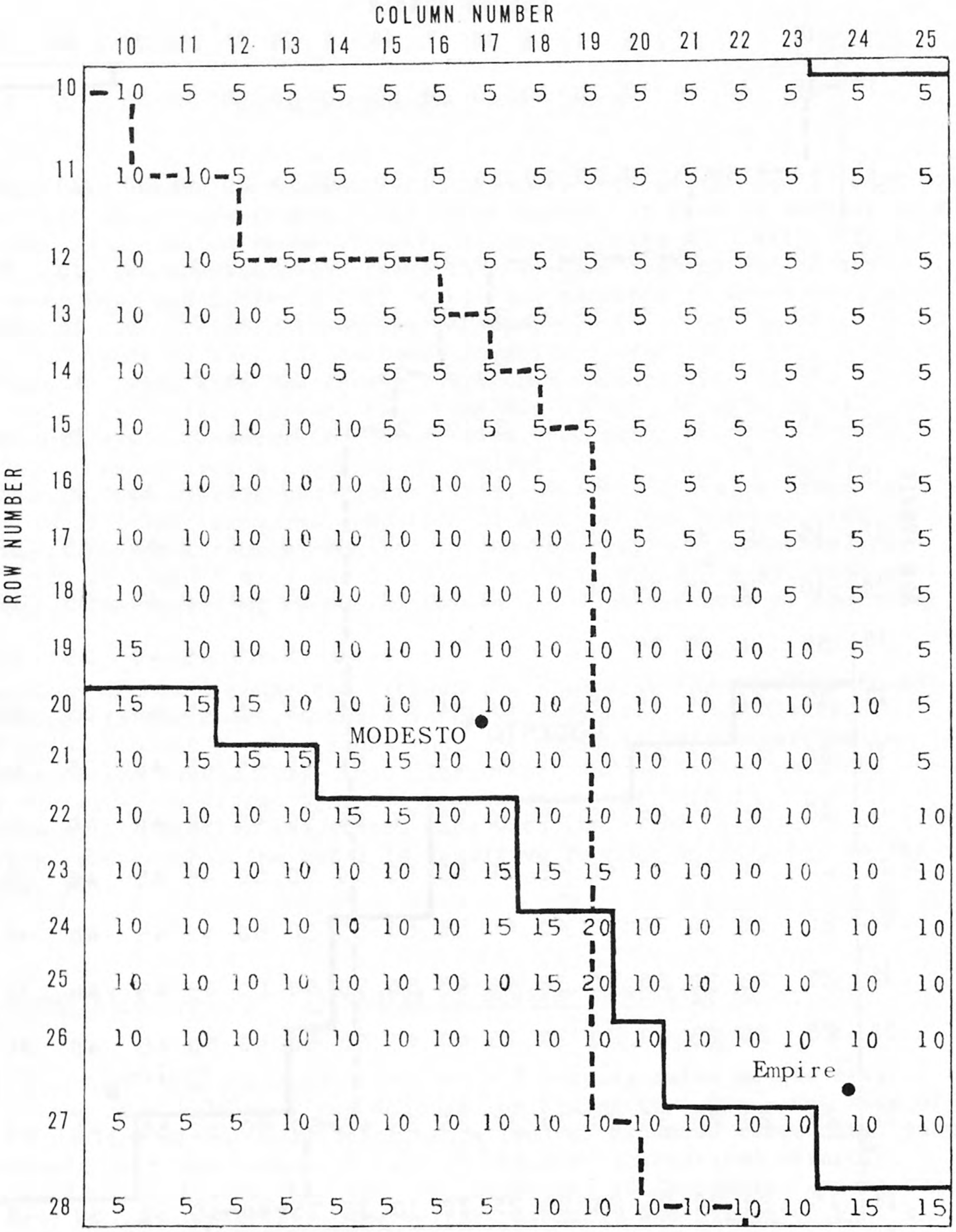
27	20	20	25	30	30	30	30	35	35	45	50	50	50	55	45	40
28	15	20	20	25	25	25	25	30	30	35	35	40	45	50	50	45

EXPLANATION

---- Approximate northeastern boundary of E-clay
—— Alinement of rivers
5 ___ Number indicating difference of 0-<5 feet
10 ___ Number indicating difference of 5-<10 feet
NOTE: Feet x 0.3048 = metres

MODEL ASSUMPTIONS
Rivers ______ absent versus present
E-clay _____ present
Pumping duration _____ 10 years

FIGURE 13.--Absolute difference between water levels as affected by the presence or absence of rivers in the model.



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27	5	5	5	10	10	10	10	10	10	10	10	10	10	10	10	10
28	5	5	5	5	5	5	5	5	10	10	10	10	10	10	15	15

EXPLANATION

---- Approximate northeastern boundary of E-clay
—— Alinement of rivers
5 ___ Number indicating difference of 0-<5 feet
10 ___ Number indicating difference of 5-<10 feet
NOTE: Feet x 0.3048 = metres

MODEL ASSUMPTIONS
Rivers____present
E-clay____present
Pumping duration___
___10 years

FIGURE 14.--Absolute difference between water levels affected by a high stage and a low stage in the rivers.

CALIBRATION

The ultimate purpose of this model is to predict changes in water levels in the aquifer caused by changes in stresses on the system. Before the model can be used for prediction, it must be calibrated; that is, water levels simulated by the stressed model must match measured water levels at any chosen time. The period chosen to stress this model was spring 1952 to spring 1962, and the time chosen for matching simulated water levels with measured water levels was spring 1962.

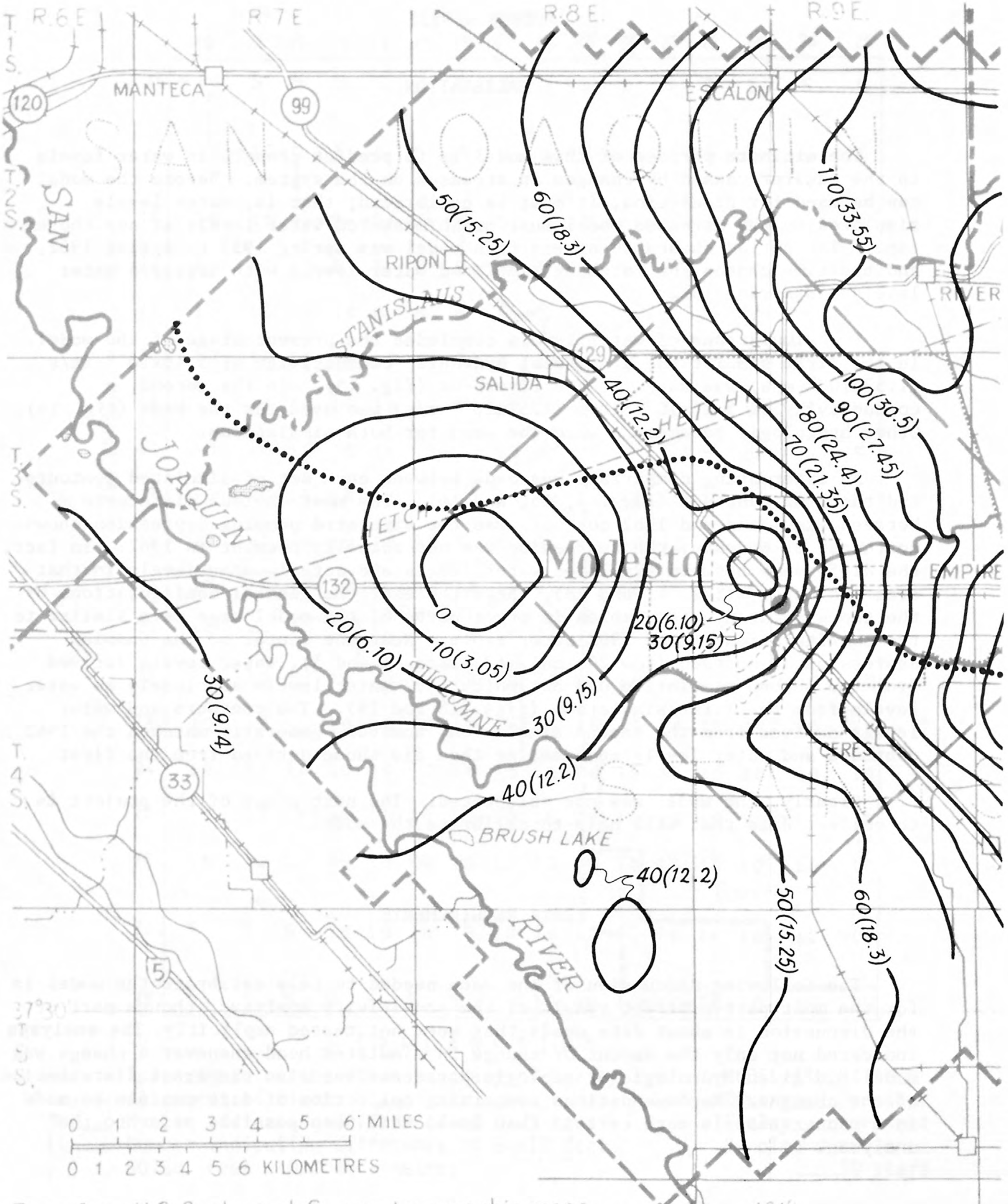
Two simulations of water levels concluded the present stage of the model. In the first simulation, a vertical hydraulic conductivity of $5.16\text{x}10^{-6}$ ft/s ($1.57\text{x}10^{-6}$ m/s) was used for the riverbeds (fig. 15). In the second, a conductivity of $5.16\text{x}10^{-4}$ ft/s ($1.57\text{x}10^{-4}$ m/s) was used for the beds (fig. 16). Other hydrologic parameters were the same for both simulations.

An interesting comparison was made between each set of simulated contours and the 1962 contours (figs. 5, 15, and 16). The most obvious difference between simulated and 1962 contours was the simulated pumping depression shown northwest of Modesto; the depression was not actually present in 1962. In fact, the difference between simulated water levels and actual water levels in that area was large (figs. 17 and 18). Nevertheless, the general configurations of the two simulated water tables in other parts of the model area were similar to the configuration of the 1962 water table. Near the center of the pumping depression at Modesto (row 20, col. 17, figs. 1 and 5), water levels derived from the second simulation did not match 1962 water levels as closely as water levels from the first simulation (figs. 18 and 19). The contours and water levels derived from the second simulation, however, generally matched the 1962 contours and water levels much better than did those derived from the first.

Clearly, the model was not calibrated. The next stage of the project is to collect data that will help to calibrate the model.

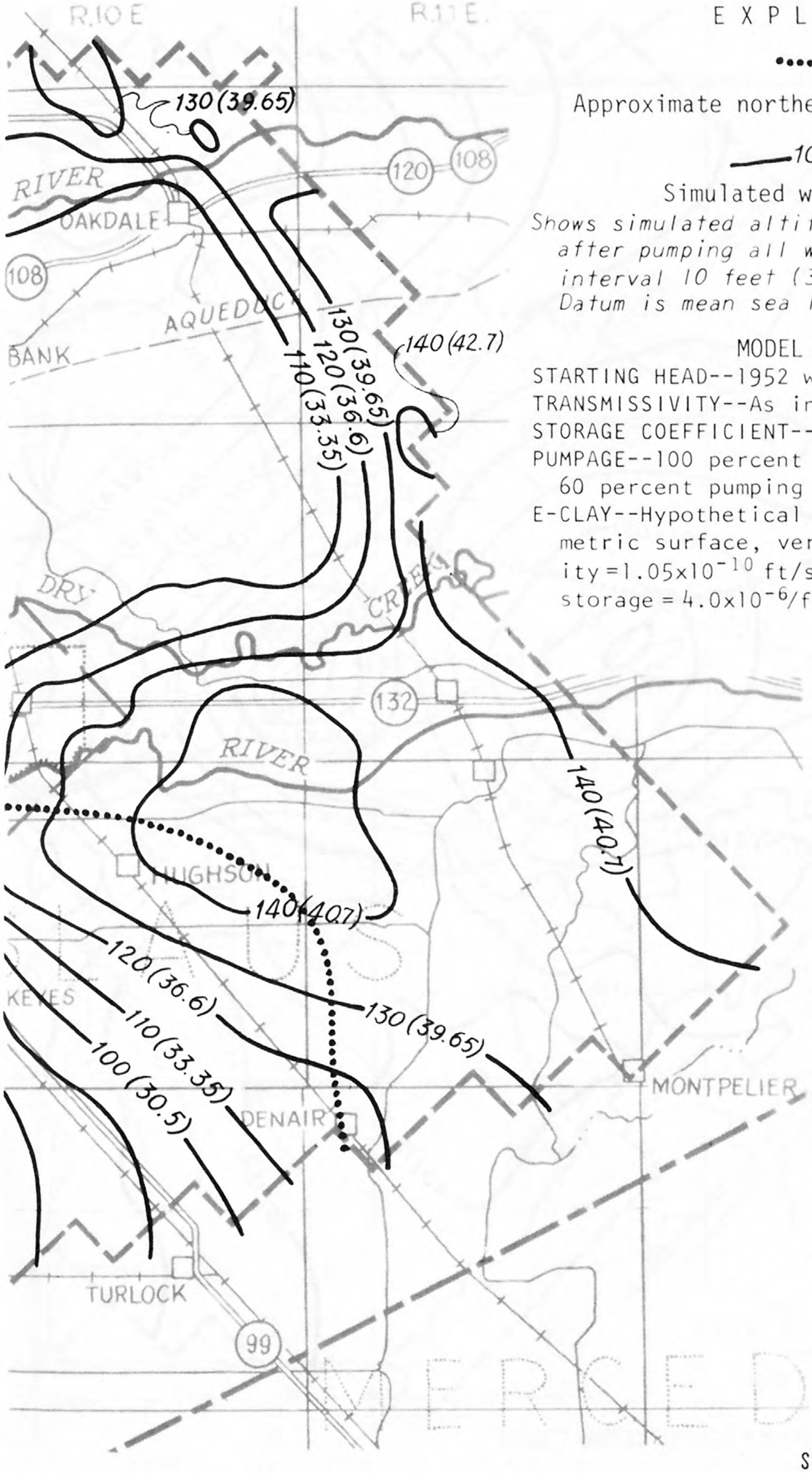
DATA REQUIREMENTS

The following discussion of the data needed to help calibrate the model is for the most part a direct result of the sensitivity analyses, though part of the discussion is about data needs that were not tested explicitly. The analyses indicated not only the amount of change in simulated head whenever a change was made in a given hydrologic or geologic parameter but also the areal distribution of the changes. Recommendations concerning collection of data can now be made in a manner that is more certain than would have been possible prior to the analyses.



Base from U.S. Geological Survey topographic maps

FIGURE 15.--Simulated altitude of water table after pumping wells for



EXPLANATION

••••••••••••••

Approximate northeastern boundary of E-clay

—— *100(30.5)* ——

Simulated water-level contour

Shows simulated altitude of water-level contour after pumping all wells for 10 years. Contour interval 10 feet (3.05 metres). Datum is mean sea level

MODEL ASSUMPTIONS

STARTING HEAD--1952 water levels

TRANSMISSIVITY--As indicated in figure 2

STORAGE COEFFICIENT--As indicated in figure 3

PUMPAGE--100 percent pumping of Modesto wells, 60 percent pumping of all other wells

E-CLAY--Hypothetical configuration of potentiometric surface, vertical hydraulic conductivity$=1.05\times10^{-10}$ ft/s (3.2×10^{-11} m/s). Specific storage $= 4.0\times10^{-6}$/ft (1.2×10^{-6}/m) (elastic). Gradual changes in thickness near edge of E-clay

RIVERS--Average head, vertical hydraulic conductivity $=5.16\times10^{-6}$ ft/s (1.57×10^{-6} m/s)

BOUNDARIES--Constant head along north, south, and west boundaries

— — — — —

Boundary of model

—— ——

Boundary of area of primary interest near Modesto

··························

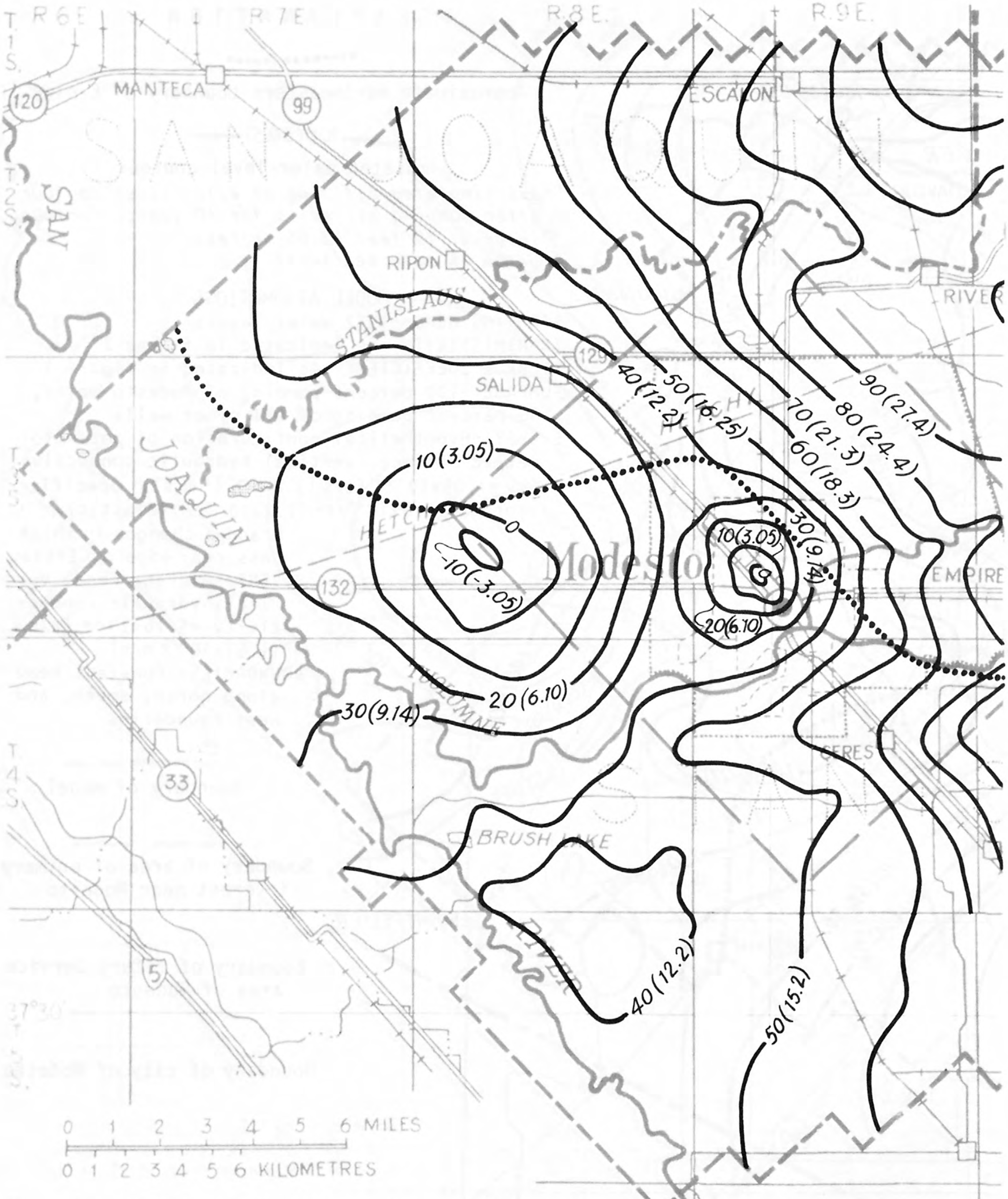
Boundary of future service area of Modesto

- - - - - - - - -

Boundary of city of Modesto

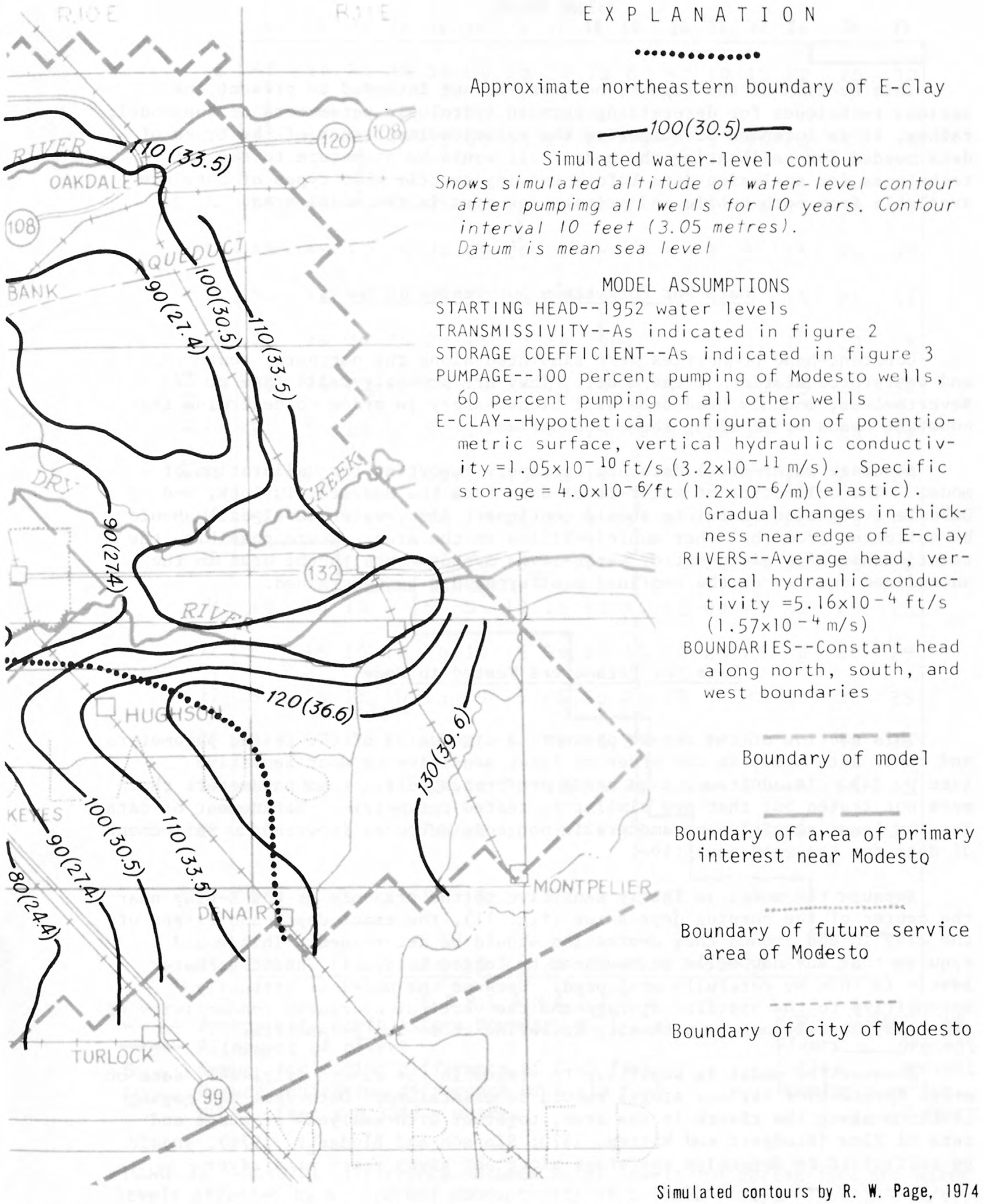
Simulated contours by R. W .Page, 1974

10 years, using small values for riverbed hydraulic conductivity.



Base from U.S. Geological Survey topographic maps

FIGURE 16.--Simulated altitude of water table after pumping wells for



EXPLANATION

Approximate northeastern boundary of E-clay

100(30.5)

Simulated water-level contour

Shows simulated altitude of water-level contour after pumpimg all wells for 10 years. Contour interval 10 feet (3.05 metres). Datum is mean sea level

MODEL ASSUMPTIONS

STARTING HEAD--1952 water levels

TRANSMISSIVITY--As indicated in figure 2

STORAGE COEFFICIENT--As indicated in figure 3

PUMPAGE--100 percent pumping of Modesto wells, 60 percent pumping of all other wells

E-CLAY--Hypothetical configuration of potentiometric surface, vertical hydraulic conductivity $=1.05\times10^{-10}$ ft/s $(3.2\times10^{-11}$ m/s). Specific storage $=4.0\times10^{-6}$/ft $(1.2\times10^{-6}$/m) (elastic). Gradual changes in thickness near edge of E-clay

RIVERS--Average head, vertical hydraulic conductivity $=5.16\times10^{-4}$ ft/s $(1.57\times10^{-4}$ m/s)

BOUNDARIES--Constant head along north, south, and west boundaries

Boundary of model

Boundary of area of primary interest near Modesto

Boundary of future service area of Modesto

Boundary of city of Modesto

Simulated contours by R. W. Page, 1974

10 years, using large values for riverbed hydraulic conductivity.

This section of the report, however, is not intended to present the various techniques for determining certain hydrologic parameters of the model; rather, it is intended to summarize the relative importance of the types of data needed for calibrating the model. It would be premature to suggest techniques for analyzing data before knowing exactly what types of data are available from both public and private agencies in the model area.

Data For Parameters Not Tested in Model

Constant-head boundaries were simulated along the northern, southern, and western boundaries of the model. They are probably valid (see p. 17). Nevertheless, monthly head data will be necessary in order to determine that constant heads exist along those boundaries.

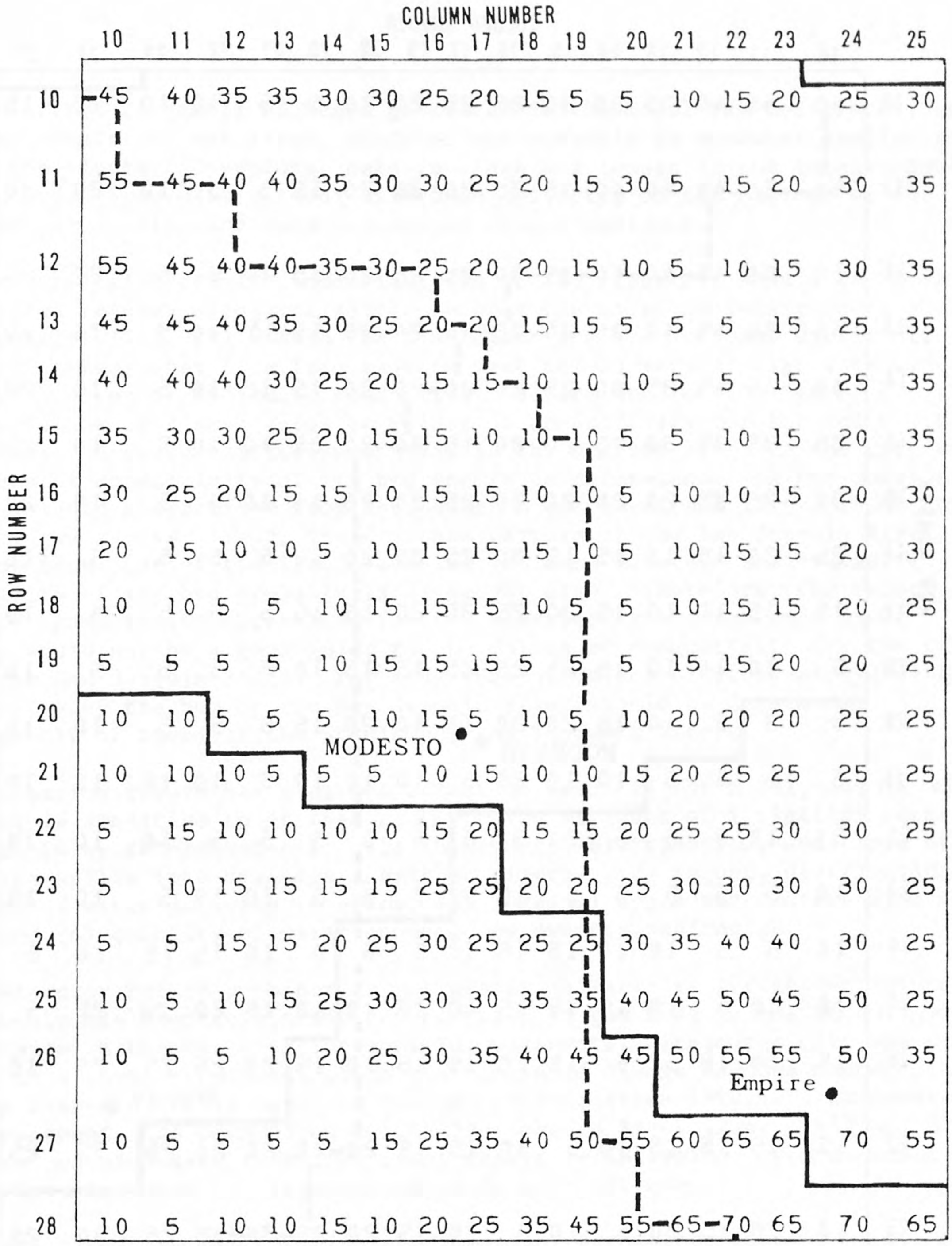
Accurate water-level data are extremely important for calibration of a model. The collection of water-level data from the Modesto, Turlock, and Oakdale Irrigation Districts should continue. Also, water-level data should be collected from the other municipalities in the area. Where possible, the relationship of a given set of water-level measurements to the head in the unconfined aquifer or the confined aquifer should be determined.

Data For Parameters Tested in Model

This section of the report presents a discussion of the tested parameters and their data needs in the order of least sensitive to most sensitive (see p. 24). In addition, data needs are presented for some parameters that were not tested but that are similar to tested parameters. Refinement of data for the least sensitive parameters is not considered as important as refinement of data for the most sensitive.

Because the model is fairly sensitive to the presence of the E-clay near the center of the pumping depression (fig. 11), the exact depth and extent of the clay in and around that depression should be determined. This would require that any new wells in the area be logged in detail, and that water levels in them be carefully monitored. Because the model is virtually insensitive to the specific storage and the vertical hydraulic conductivity of the clay, it will not be necessary to refine those two parameters.

Because the model is sensitive to stages in the rivers (fig. 14), data on stage duration of various stages should be maintained. Data from the gaging stations along the rivers in the area, together with analyses of stage and rate of flow (Blodgett and Mitten, 1970; Simpson and Blodgett, 1974), should be sufficient to determine the stage along any given reach of a river.



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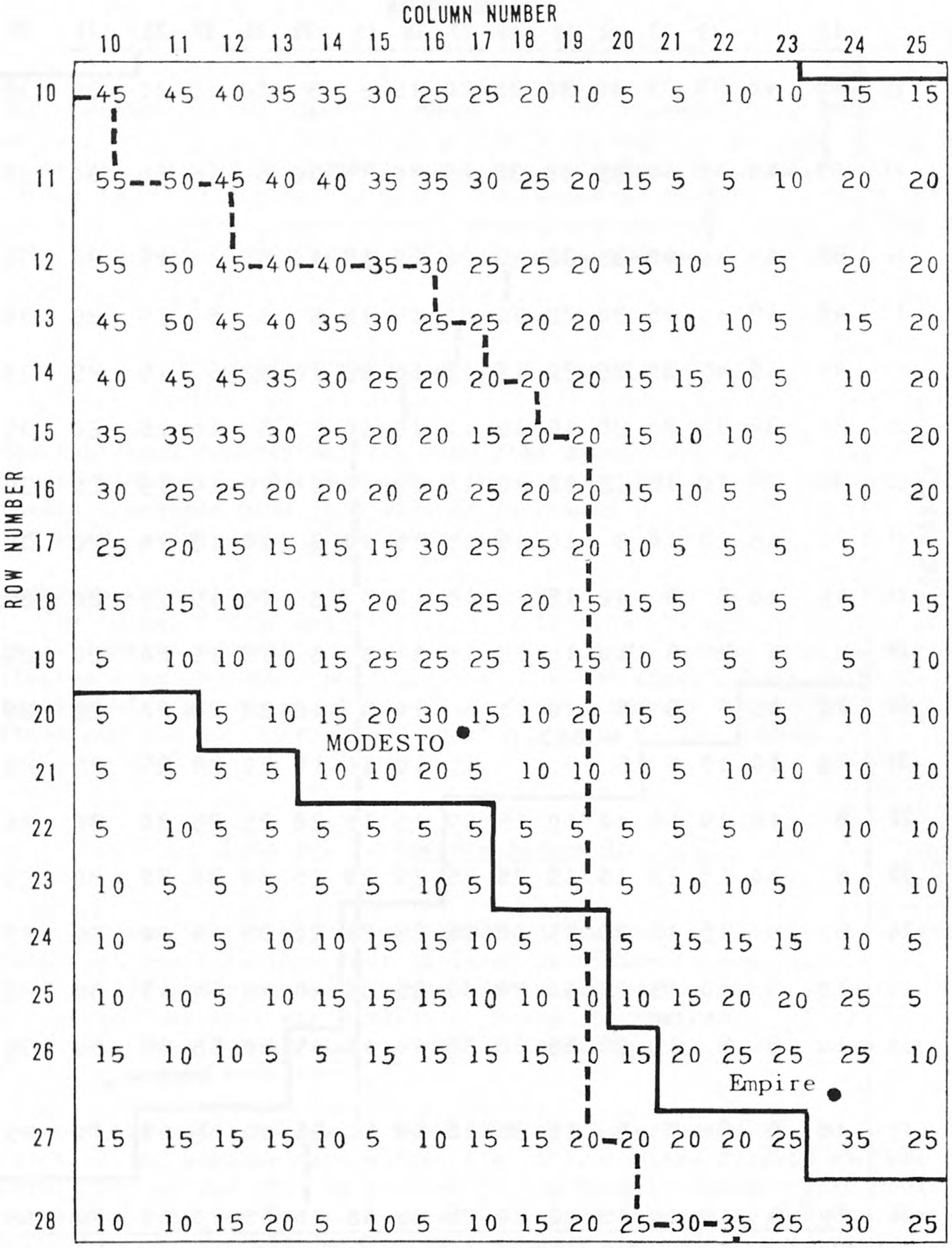
27	10	5	5	5	5	15	25	35	40	50	55	60	65	65	70	55
28	10	5	10	10	15	10	20	25	35	45	55	65	70	65	70	65

EXPLANATION

---- Approximate northeastern boundary of E-clay
—— Alinement of rivers
5 ___ Number indicating difference of 0-<5 feet
10 ___ Number indicating difference of 5-<10 feet
NOTE: Feet x 0.3048 = metres

MODEL ASSUMPTIONS
Rivers____present
E-clay____present
Pumping duration____10 years

FIGURE 17.--Absolute difference between water levels for spring 1962 and water levels affected by a riverbed conductivity of 5.16×10^{-6} ft/s (1.57×10^{-6} m/s).



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25	10	10	5	10	15	15	15	10	10	10	10	15	20	20	25	5
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27	15	15	15	15	10	5	10	15	15	20	20	20	20	25	35	25
28	10	10	15	20	5	10	5	10	15	20	25	30	35	25	30	25

EXPLANATION

---- Approximate northeastern boundary of E-clay
—— Alinement of rivers
5 ___ Number indicating difference of 0-<5 feet
10 ___ Number indicating difference of 5-<10 feet
NOTE: Feet x 0.3048 = metres

MODEL ASSUMPTIONS
Rivers____present
E-clay____present
Pumping duration__
____10 years

FIGURE 18.--Absolute difference between water levels for spring 1962 and water levels affected by a riverbed conductivity of 5.16×10^{-4} ft/s (1.57×10^{-4} m/s).

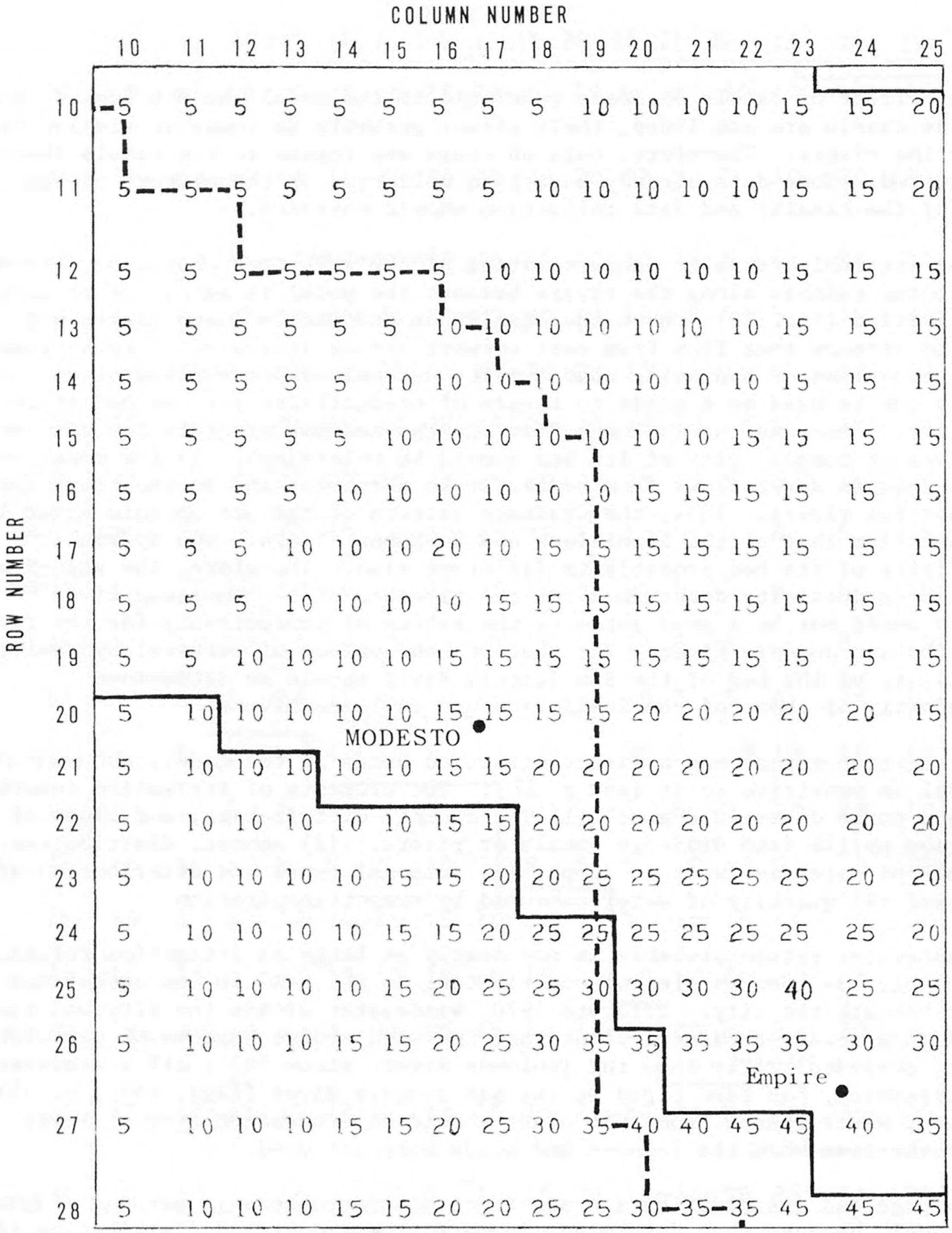
The effect of canals on heads generated in the model was not tested, but where the canals are not lined, their effect probably is somewhat similar to that of the rivers. Therefore, data on stage and losses in the canals should be collected. Some data already have been collected on the history of the lining of the canals, and data collection should continue.

The vertical hydraulic conductivities of the riverbeds should be determined for selected reaches along the rivers because the model is sensitive to such conductivities (fig. 19). Both the Stanislaus and the Tuolumne Rivers are regulated streams that flow from east to west across very similar rock types. Therefore, values of hydraulic conductivity determined for the bed of one river probably can be used as a guide to values of conductivity for the bed of the other river. Because the Tuolumne River is the nearest river to the city wells, the values of conductivity of its bed should be determined. In the model area, the San Joaquin River flows from southeast to northwest and is the trunk for the other two rivers. Thus, the drainage pattern of the San Joaquin River is different from that of the Stanislaus and Tuolumne Rivers. The hydraulic conductivity of its bed probably is different also. Therefore, the values of hydraulic conductivity determined for the riverbed of the Tuolumne River probably would not be a good guide to the values of conductivity for the riverbed of the San Joaquin River. For that reason, values of vertical hydraulic conductivity of the bed of the San Joaquin River should be determined independently of those of the Stanislaus and Tuolumne Rivers.

Irrigation return has a direct effect on heads in the model, and therefore the model is sensitive to it (see p. 27). The elements of irrigation return that need to be determined are: (1) The amount, distribution, and times of irrigation spills into drainage canals or rivers, (2) amount, distribution, and times of water delivery to crops, (3) seasonal types and distribution of crops, and (4) quantity of water consumed by evapotranspiration.

Wastewater return probably is not nearly as large as irrigation return, but probably has been an element contributing to the head in the unconfined aquifer beneath the city. Prior to 1970, wastewater within the city was either treated in a sewage-treatment plant that included sludge lagoons and percolation ponds or dumped directly into the Tuolumne River; since 1970, all wastewater, after treatment, has been piped to the San Joaquin River (Page, 1972, p. 31). Therefore, water losses from that plant should be determined from at least 1950 to the time when the lagoons and ponds were not used.

Pumpage and its distribution are important parameters in any type of groundwater model, because they determine, in part, the amount and distribution of head decline. Some pumpage data have been collected from the Modesto and Turlock Irrigation Districts and the city of Modesto; such data collection should continue. Also, all available pumpage and pumpage-distribution data should be collected from the other municipalities in the model area and from private owners of wells. These data should be collected in a continuing manner starting from at least 1950. Where possible, the source of pumpage, whether from the unconfined aquifer or the confined aquifer, should be determined.



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27	5	10	10	10	15	15	20	25	30	35	40	40	45	45	40	35
28	5	10	10	10	15	15	20	20	25	25	30	35	35	45	45	45

EXPLANATION

---- Approximate northeastern boundary of E-clay
——— Alinement of rivers
5 ___ Number indicating difference of 0-<5 feet
10___ Number indicating difference of 5-<10 feet
NOTE: Feet x 0.3048 = metres

MODEL ASSUMPTIONS
Rivers_____present
E-clay_____present
Pumping duration__
_____10 years

FIGURE 19.--Absolute difference between water levels affected by vertical conductivities of 5.16x10^{-4} ft/s (1.57x10^{-4} m/s) and of 5.16x10^{-6} ft/s (1.57x10^{-6} m/s).

The transmissivity and the storage coefficient of an aquifer determine the rate at which a given cone of depression expands, and thus the times at which it reaches areas of recharge or discharge. In this manner, they affect the rates of decline or rise in head in an aquifer and the hydraulic gradients. Because the model is quite sensitive to transmissivity and the storage coefficient (figs. 8 and 9), their values should be determined as accurately as possible. Values for transmissivity and storage will probably be determined in greater detail in and near the city than in areas away from it because those values near the city have a more immediate effect on the rise and decline of heads in city wells than do those away from it.

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