AN EFFICIENT DETERMINISTIC-PROBABILISTIC APPROACH TO MODELING REGIONAL GROUND-WATER FLOW: APPLICATION TO OWENS VALLEY, CALIFORNIA

U.S. GEOLOGICAL SURVEY

Open-File Report 88-91

Prepared in cooperation with

INYO COUNTY and the

LOS ANGELES DEPARTMENT OF WATER AND POWER

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By *Gary L. Guymon* and *Chung-Cheng Yen*

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CONVERSION FACTORS

Metric (SI) units are used in this report. For readers who prefer inch-pound units, the conversion factors for the terms used in this report are listed below.

Multiply	By	To obtain
km (kilometer)	0.6214	mile
m (meter)	3.281	feet

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

The applicability of a deterministic-probabilistic model for predicting water tables in southern Owens Valley, California, is evaluated. The model is based on a two-layer deterministic model that is cascaded with a two-point probability model. To reduce the potentially large number of uncertain variables in the deterministic model, lumping of uncertain variables was evaluated by sensitivity analysis to reduce the total number of uncertain variables to three variables: hydraulic conductivity, storage coefficient or specific yield, and source-sink function. Results demonstrate that lumping of uncertain parameters reduces computational effort with little sacrifice in precision. Simulated spatial coefficients of variation for water table temporal position in most of the basin is small, which suggests that deterministic models can predict water

tables in these areas with good precision. However, in several important areas where pumping occurs or the geology is complex, the simulated spatial coefficients of variation are high, which indicates that the two-point probability method is inaccurate (over estimates of coefficients of variation) or more precise deterministic models may be required to achieve desired levels of precision.

INTRODUCTION

A deterministic-probabilistic method for evaluating uncertainty in regional ground-water flow models [Yen and Guymon, 1988] is applied to the southern part of the Owens Valley, California. A quasi, three-dimensional, two-layer aquifer deterministic model is cascaded with a two-point probability model that estimates spatial solution means and standard deviations that result from uncertainty associated with deterministic parameters: hydraulic conductivity, storage coefficient, and source-sink function. The method is based on a simplified two-point estimate scheme first proposed by Rosenblueth [1975 and 1981], which requires only estimates of parameter means and their coefficients of variation. The simplified two-point probability estimate method is equivalent to a first-order analysis and results are comparable to the Monte Carlo simulation method, providing the variance of uncertain parameters is small. To accurately model a large basin, many discrete nodes are required, which potentially will result in a large computational effort. The simplified two-point estimate method requires less computational effort, therefore, it becomes a preferable alternative to the Monte Carlo simulation method or the first-order error analysis.

Owens Valley is a large ground-water basin in the eastern part of California between the Sierra Nevada on the west and the White and Inyo Mountains on the east (fig. 1). A shallow unconfined aquifer underlies most of the basin, and

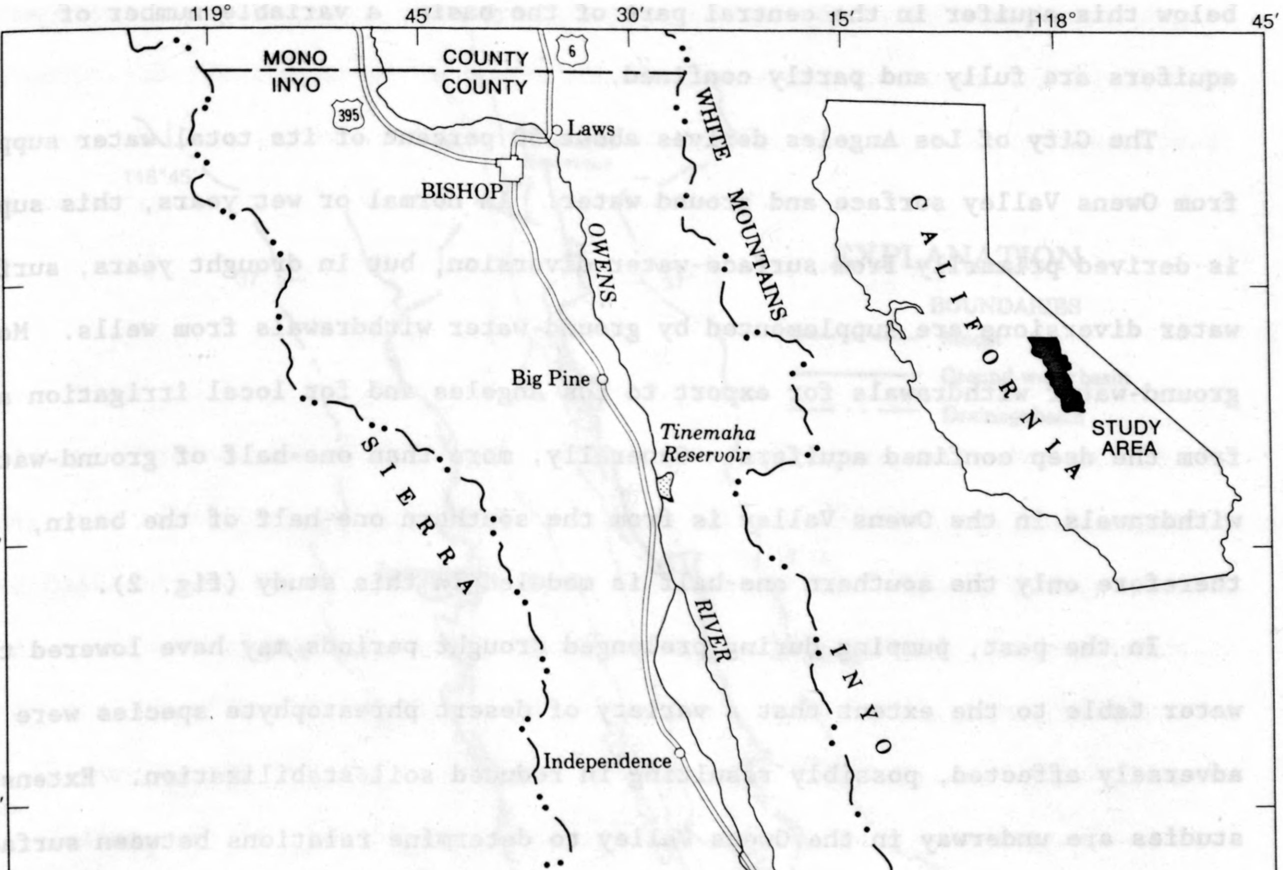

FIGURE 1.—Location of study area.

below this aquifer in the central part of the basin, a variable number of aquifers are fully and partly confined.

The City of Los Angeles derives about 60 percent of its total water supply from Owens Valley surface and ground water. In normal or wet years, this supply is derived primarily from surface-water diversion, but in drought years, surface-water diversions are supplemented by ground-water withdrawals from wells. Most ground-water withdrawals for export to Los Angeles and for local irrigation are from the deep confined aquifers. Generally, more than one-half of ground-water withdrawals in the Owens Valley is from the southern one-half of the basin, therefore only the southern one-half is modeled in this study (fig. 2).

In the past, pumping during prolonged drought periods may have lowered the water table to the extent that a variety of desert phreatophyte species were adversely affected, possibly resulting in reduced soil stabilization. Extensive studies are underway in the Owens Valley to determine relations between surface vegetation and ground-water supply. The purpose of these studies is to develop management plans that will permit pumpage of ground water, while ensuring survival of surface vegetation. One of the tools for developing and evaluating management plans will be a series of numerical models that relate ground-water responses to evapotranspiration by vegetation. Because desert phreatophytes may be sensitive to the depth of the water table, numerical modeling needs to be accurate and modeling uncertainty needs to be systematically evaluated. This study was done by the U.S. Geological Survey in cooperation with Inyo County and the Los Angeles Department of Water and Power.

DETERMINISTIC MODEL

The ground-water basin is modeled as a two-layer system that consists of the shallow unconfined aquifer and deep confined aquifers, which are modeled as a

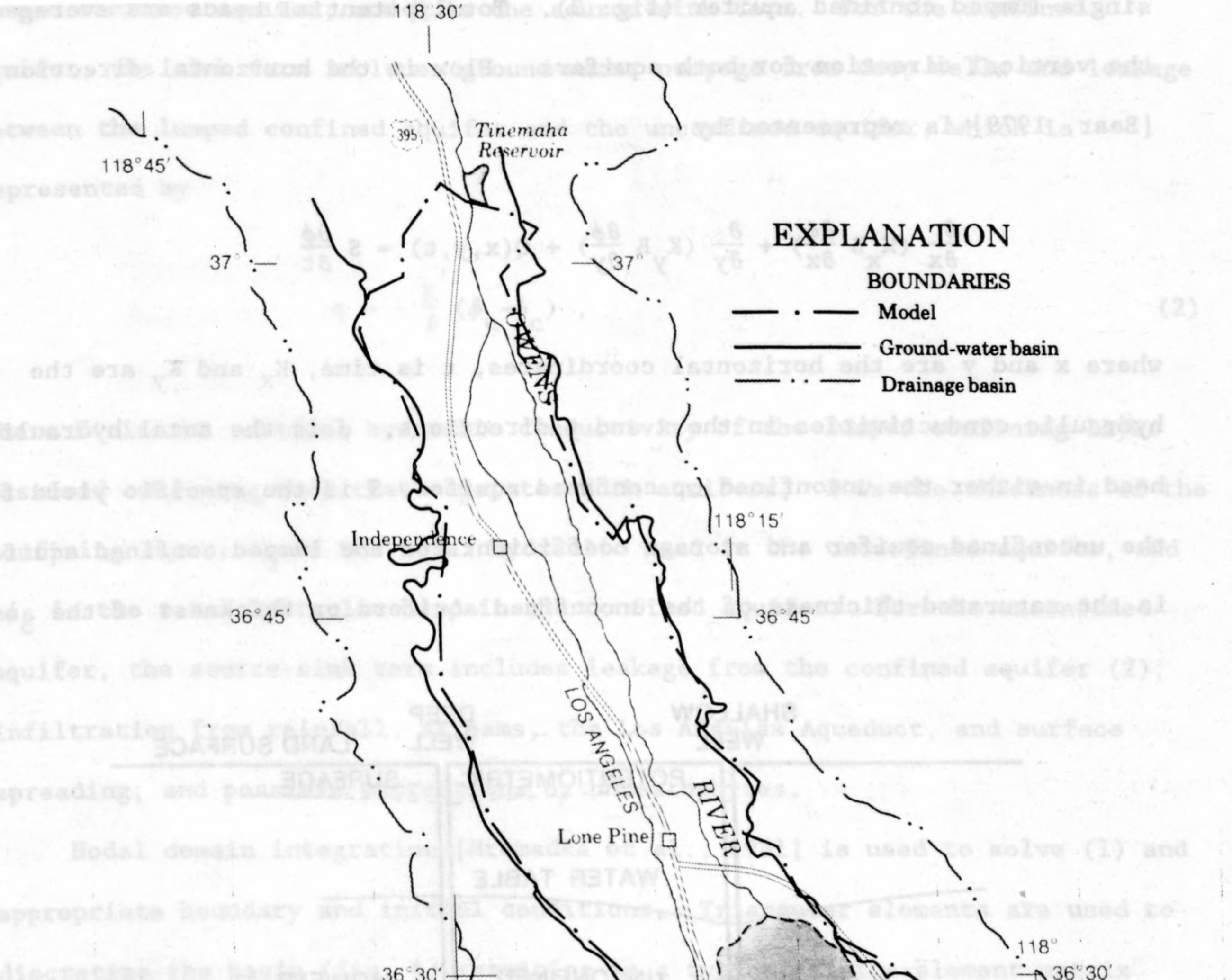

FIGURE 2.—Southern Owens Valley ground-water basin.

single-lumped confined aquifer (fig. 3). Total potential heads are averaged in the vertical direction for both aquifers. Flow in the horizontal direction [Bear, 1979] is represented by

$$\frac{\partial}{\partial x}\left(K_x B \frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y B \frac{\partial \phi}{\partial y}\right) + Q(x,y,t) = S \frac{\partial \phi}{\partial t} \, , \qquad (1)$$

where x and y are the horizontal coordinates, t is time, K_x and K_y are the hydraulic conductivities in the x and y directions, ϕ is the total hydraulic head in either the unconfined or confined aquifer, S is the specific yield for the unconfined aquifer and storage coefficient for the lumped confined aquifer, B is the saturated thickness of the unconfined aquifers or thickness of the assumed

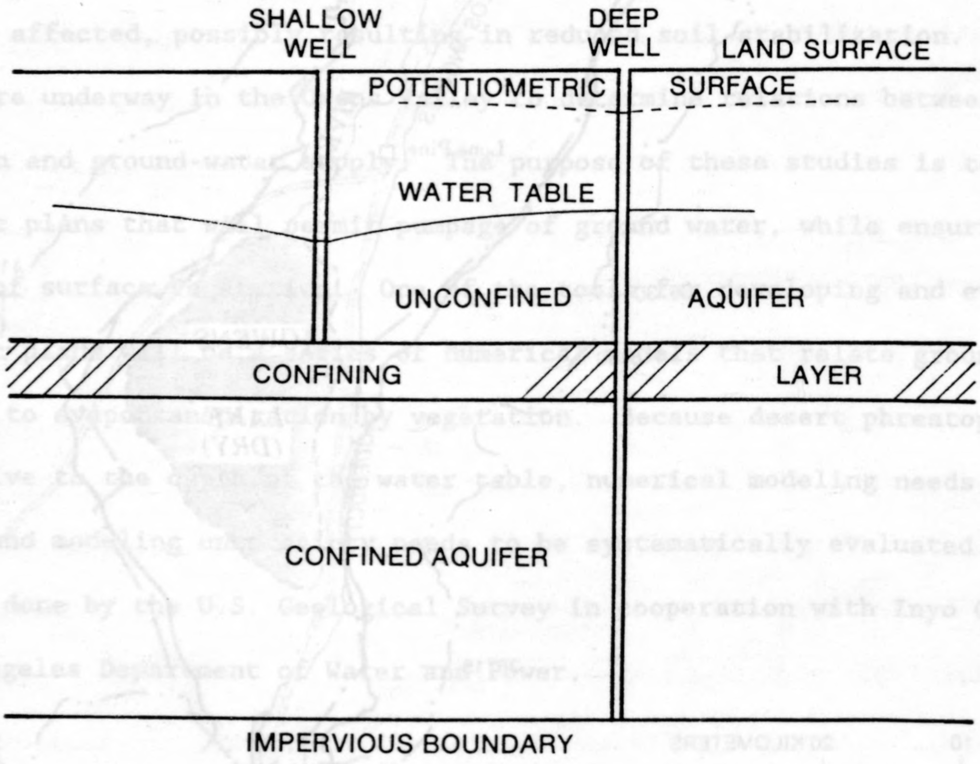

FIGURE 3.—Schematic cross section of the ground-water basin modeled as a two-layer system.

lumped confined aquifer, and Q is the source-sink term. For the confined aquifer, the sink term includes ground-water pumpage from deep wells and leakage between the lumped confined aquifer and the unconfined aquifer, which is represented by

$$q = -\frac{K'}{\ell}(\phi_u - \phi_c) , \tag{2}$$

where K' is the vertical hydraulic conductivity of the lumped confining layer (assumed confining bed) that separates both aquifers, ℓ is the thickness of the confining layer, ϕ_u is the total hydraulic head in the unconfined aquifer, and ϕ_c is the total hydraulic head in the confined aquifer. For the unconfined aquifer, the source-sink term includes leakage from the confined aquifer (2); infiltration from rainfall, streams, the Los Angeles Aqueduct, and surface spreading; and possible extractions by phreatophytes.

Nodal domain integration [Hromadka et al., 1981] is used to solve (1) and appropriate boundary and initial conditions. Triangular elements are used to discretize the basin (fig. 4) resulting in a typical finite-element matrix equation as follows:

$$[S]\{\phi\} + [P]\{\dot{\phi}\} = \{F\} , \tag{3}$$

where for a linear trial function the element conductance matrix is given by

$$[S]^e = \frac{K^e B^e}{4A^e} \begin{bmatrix} (x_{23}^2 - y_{23}^2) & -(x_{13}x_{23} + y_{13}y_{23}) & (x_{12}x_{23} + y_{12}y_{23}) \\ (\text{symmetric}) & (x_{13}^2 + y_{13}^2) & -(x_{12}x_{13} + y_{12}y_{13}) \\ & & (x^2 + y^2) \end{bmatrix} , \tag{4}$$

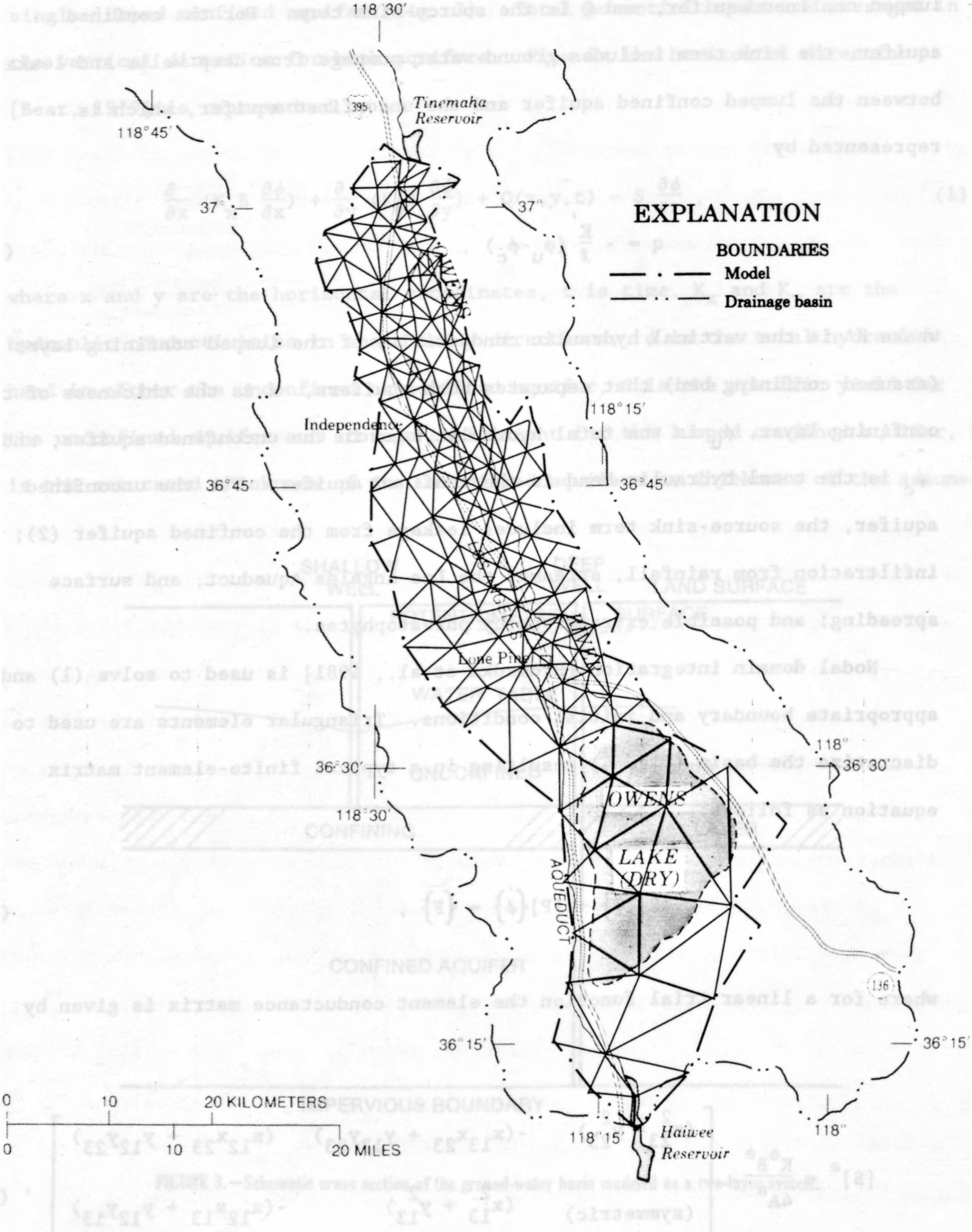

FIGURE 4.—Finite element grid used for the ground-water flow model.

and the element compacitance matrix is given by

$$[P]^e = \frac{S^e A^e}{3(\eta + 2)} \begin{bmatrix} \eta & 1 & 1 \\ 1 & \eta & 1 \\ 1 & 1 & \eta \end{bmatrix} , \qquad (5)$$

where $\dot{\phi}$ is the time derivative; e indicates that an element quantity, x_{ij} and y_{ij} are element node verticies, A^e is element area, and η is a mass lumping parameter (2, 22/7, + ∞ for Galerkin, subdomain, and integrated finite-differences schemes, respectively).

A fully explicit time advancement scheme is used to solve the temporal (or dynamic) part of (3) as follows:

$$([S] + \frac{1}{\Delta t} [P])_{t+\Delta t} \{\phi\}_{t+\Delta t} = \frac{1}{\Delta t} [P]_t \{\phi\}_t + \{F\}_{t+\Delta t} , \qquad (6)$$

where Δt is the time step size. The leakage term is satisfied by a simple iterative procedure where (1) is solved for the unconfined aquifer then the confined aquifer until (2) is satisfied (usually requiring only two or three iterations).

CALIBRATION OF DETERMINISTIC MODEL

Six subregions are defined to assign parameters used in the model as follows (fig. 5):

Upslope area. -- Most of the alluvial fans (elevation about 1,190 m or higher), which are the most extensive water-bearing formations in Owens Valley.

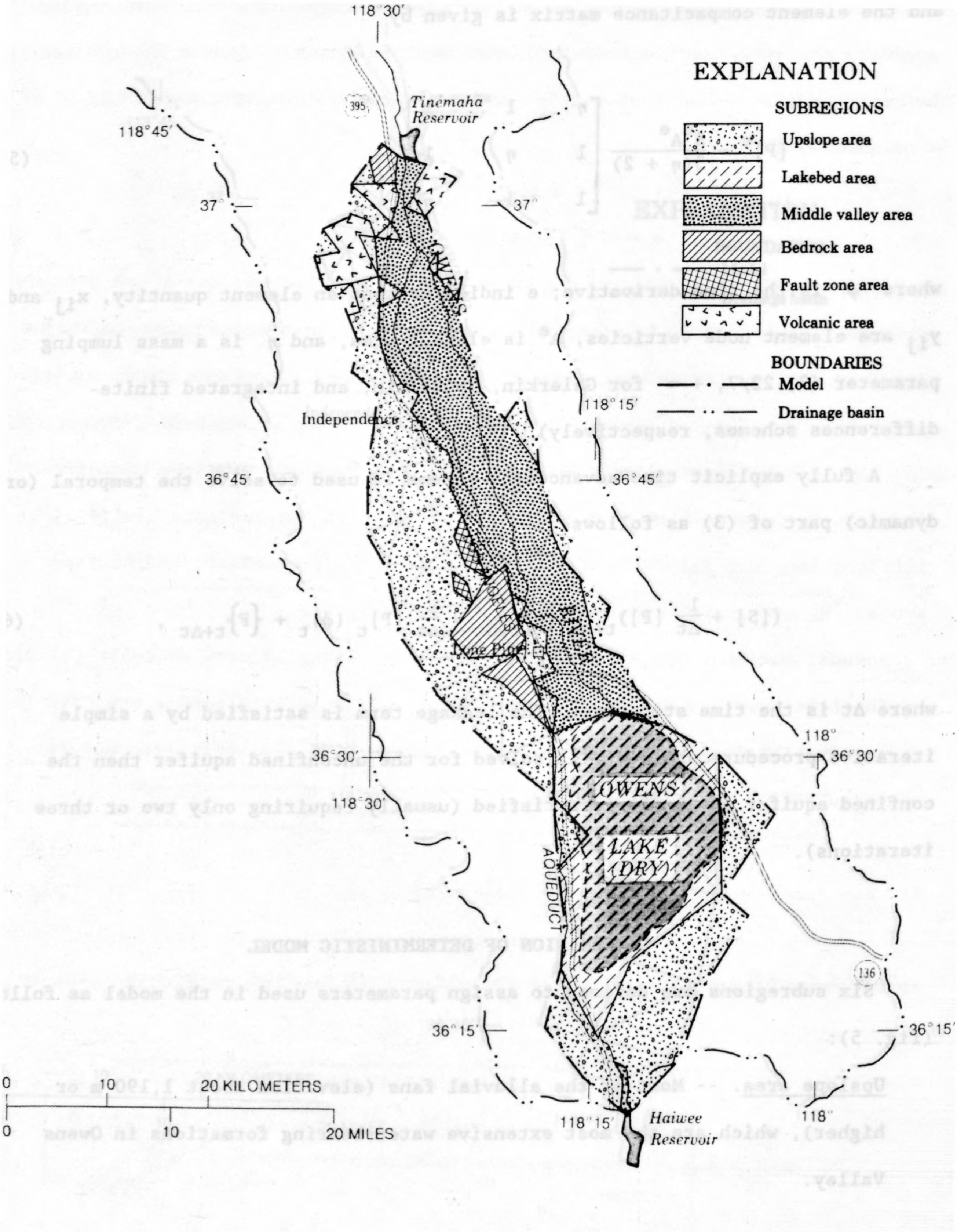

FIGURE 5.—Six representative subregions of the study area.

Lakebed area. -- Owens Lake and its surrounding area.

Valley floor area. -- Alluvial fan (elevation 1,190 m or less), which consists primarily of the areas adjacent to the Owens River and Los Angeles Aqueduct.

Bedrock area. -- Small bedrock outcrop areas near Tinemaha Reservoir and near Lone Pine.

Fault zone area. -- A small area midway between Independence and Lone Pine.

Volcanic area. -- The volcanic outcrops in the northern part of the model area.

Parameters that characterize the six subregions in the model are based on: (1) pumping tests, which were done by the Los Angeles Department of Water and Power, (2) geohydrologic information developed by Williams [1969], and (3) general data such as contained in DeWiest [1969]. Estimated parameters were used in an assumed steady-state calibration based on calendar years 1970 and 1974, which was at the beginning of increased pumping. A leakage factor of 3.47×10^{-5} cm/h was used to describe the hydraulic conductivity of the lumped confining layer separating the unconfined aquifer and the lumped confined aquifer. The precipitation, streamflow, estimated deep percolation rate, and estimated evapotranspiration (ET) rate were based on 31-year (1935-66) long-term average values [Los Angeles Department of Water and Power (LADWP), 1976]. For steady-state calibration, the precipitation rate for each subregion was interpolated from a 31-year mean isohyetal map, and it was assumed that 30 percent of precipitation percolated to the water table. Deep percolation from streamflow was estimated from prior studies (LADWP, 1976) and a rate of 0.018 $m^3/s/km$ was assumed. Deep percolation from the Los Angeles Aqueduct was assumed to be 0.035 $m^3/s/km$ based upon prior studies. An evapotranspiration rate is assumed as a linear function of the depth to the water table. Data on average pumpage of each well was based on a 10-year (prior to the 1970 calendar year) averaged value.

Source-sink data were estimated for each finite-element node. Nodal control volumes are constructed by joining the centroids of the triangular finite elements to the midpoints of the corresponding sides. This creates polygonal control volumes that surround each finite-element nodal point. The source and sink terms in a control volume are calculated in terms of a net point source or sink for that nodal point, which represents the net flux for that control volume.

The prescribed boundary conditions are assumed to be constant heads at Tinemaha and Haiwee Reservoirs (fig. 2).

After minor calibration of estimated storage and transmissivity, simulated water-table levels in the unconfined aquifer closely matched measured water-table levels. In volcanic areas, differences between simulated and measured water levels were large, ranging between 2 and 3 m; however, in areas where vegetation is assumed to be sensitive to the depth of the water table, differences between simulated and measured water levels were small, ranging between 0.3 and 0.6 m. Comparisons between estimated potentiometric surfaces for the confined aquifer were not made because of the complex nature of the system of confined and semiconfined aquifers represented by an assumed single-lumped confined aquifer system. Calibrated hydraulic conductivity, specific yield, and storage coefficients for the various areas of the basin are shown in table 1.

Table 1. Representative parameters of the study area

Subregion	Unconfined aquifer		Confined aquifer	
	Hydraulic conductivity (m/d)	Specific yield	Hydraulic conductivity (m/d)	Storage coefficient
Upslope area	1.67	0.250	1.67	0.250
Lakebed area	0.83×10^{-2}	0.010	0.83×10^{-2}	0.010
Valley floor area	0.83×10^{0}	0.030	0.83×10^{0}	0.010
Bedrock area	0.83×10^{-5}	0.005	0.83×10^{-5}	0.005
Fault zone area	0.83×10^{-5}	0.005	0.83×10^{-5}	0.005
Volcanic area	0.83×10^{1}	0.300	0.83×10^{1}	0.300

Additionally, a transient calibration of the deterministic model was conducted from data for 1971-81. Water levels in the basin generally declined to a low during 1976-77 and recovered by 1980 to pre-1971 conditions. The 1971 water levels are similar to the pre-aqueduct high water levels reported by Lee [1912]. Monthly rainfall, streamflow, aqueduct flow, and water pumpage data were developed and distributed to model nodes as described above. Monthly evapotranspiration was estimated by using measured monthly air temperature and a simple relation between measured evapotranspiration at three micrometeorological test sites [Duell, 1988]. At these three sites, a variety of other data was collected during 1984-86 such as water levels, soil-moisture profiles, vegetation-soil moisture parameters, plant canopy information, and laboratory measurement of hydraulic properties of soils. Data used to calibrate the model were obtained from test sites and wells (observation points shown in figure 6). Minor calibration of parameters and boundary conditions were required to simulate measured water levels.

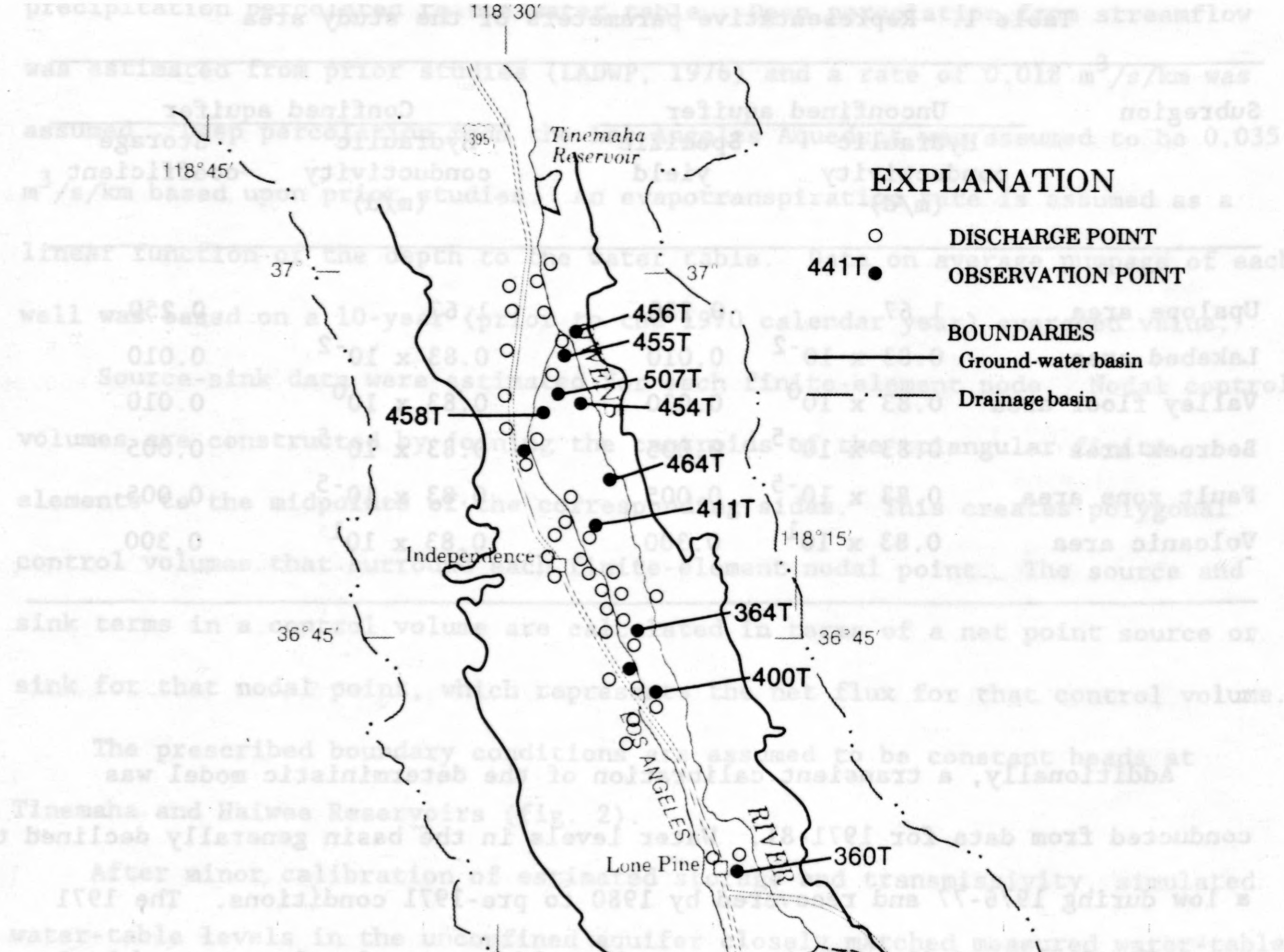

FIGURE 6.—Location of discharge nodal points and observation points.

Figure 7 shows a comparison of simulated and measured water levels for shallow test hole 411T. In general, the results from the transient model simulates the 1971 through 1981 water-table conditions. The deviation between the measured water table and simulated results primarily are due to the simplicity of the deterministic ground-water model and lack of accurate evapotranspiration, rainfall, and deep percolation functions for the entire ground-water basin. The model developed is adequate for the objectives of this research, which was to develop an efficient probabilistic approach.

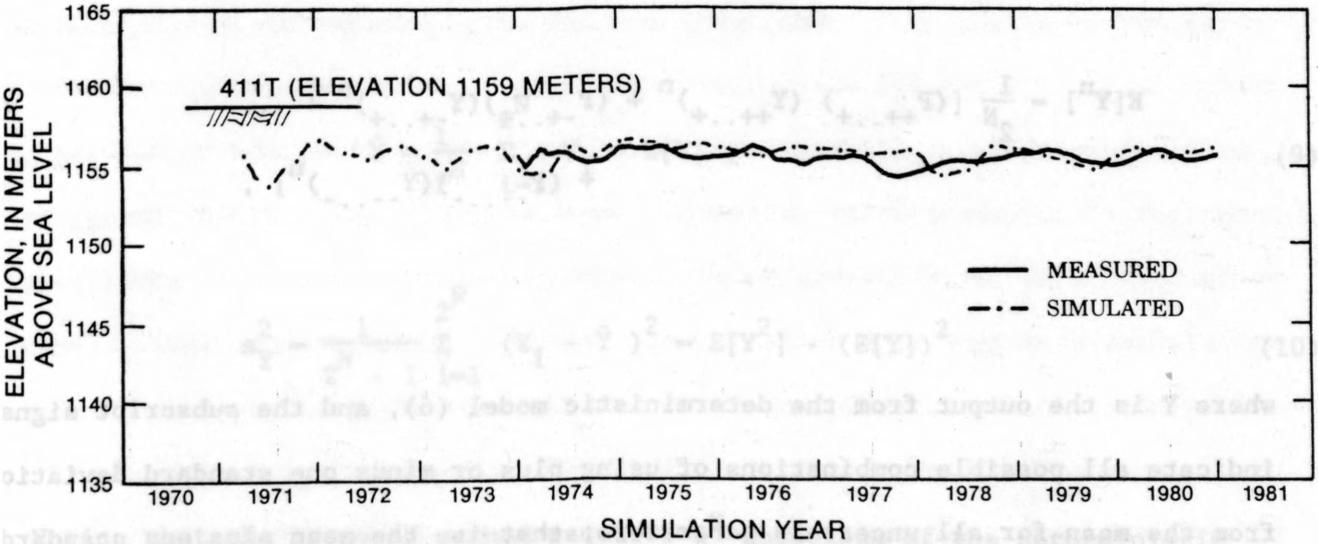

FIGURE 7.—Comparison of simulated and measured water levels for transient calibration for shallow test hole 411T, 1971-81.

APPLICATION OF A SIMPLIFIED

DETERMINISTIC-PROBABILISTIC MODEL TO OWENS VALLEY

A simplified two-point probability estimate method [Yen and Guymon, 1988] is applied which is similar to a linear analysis of error. The term "two-point" means that the mean and standard deviation are used to describe the probabilistic or uncertain aspect of the model parameters and boundary conditions, for example, the two chosen points are symmetrical about the mean. As shown by Yen and Guymon [1988], the appropriate equations for the n-th statistical moment of results for N uncertain variables is

$$E[Y^n] = \frac{1}{2^N} [(P_{++..+}) (Y_{++..+})^n + (P_{-+..+})(Y_{-+..+})^n + \ldots + (P_{--..-})(Y_{--..-})^n] , \quad (7)$$

where Y is the output from the deterministic model (6), and the subscript signs indicate all possible combinations of using plus or minus one standard deviation from the mean for all uncertain parameters; that is, the mean plus one standard deviation of parameter. Variables P, represent the correlation parameter between uncertain variables where

$$P_{++..+} = 1 + \sum_{i,j}^{N} \alpha_i \alpha_j f_{ij} \rho_{ij} , \quad (8)$$

where

$$f_{ij} = \begin{cases} 0, & i \geq j \\ 1, & i < j \end{cases}$$

$$\alpha_i = \begin{cases} 1, \text{ if i-th subscript of } P_{++..+} \text{ is a positive sign} \\ -1, \text{ if i-th subscript of } P_{++..} \text{ is a negative sign} \end{cases}$$

and ρ_{ij} is the correlation between uncertain variables i and j.

In this application, it is assumed that there is no correlation between the uncertain variables studied, for example, $\rho_{ij} \equiv 0$, and only the mean and variance of the results are computed

$$\bar{Y} = \frac{1}{2^N} \sum_{i=1}^{2^N} Y_i = E[Y], \tag{9}$$

$$s_Y^2 = \frac{1}{2^N - 1} \sum_{i=1}^{2^N} (Y_i - \bar{Y})^2 = E[Y^2] - (E[Y])^2. \tag{10}$$

Notice that the proposed method requires 2^N solutions of the deterministic model. Both the mean and variance are functions of discrete nodes and discrete solutions of time step, Δt.

The Owens Valley ground-water basin has been descretized into 350 nodes, (fig. 4). For the area of influence of each node, there are potentially a number of uncertain parameters or boundary conditions: hydraulic conductivity, storage coefficient, thickness of the lumped aquifer, evapotranspiration, deep percolation from several sources, and ground-water pumpage. Assuming the variance of each of these factors was different for each node, N of (7) might be on the order of 2,450, which means that (6) would have to be solved $2^{2,450}$ times (which is infinite for all practical purposes). Clearly as pointed out by Yen and Guymon [1988] the Monte Carlo approach would be preferable.

To reduce these computational problems, grouping of uncertain parameters is proposed. Different basins will require different approaches depending on the quality of data available, the size and geological complexity of the basin, and the modeling objectives. The approach applied here is applicable to problems of the same nature as the Owens Valley study. The objective is to reduce the size of the problem to three uncertain variables requiring eight solutions of (6). This is done by assuming that boundary conditions and geometric variables are accurately known and by investigating errors in the source-sink term, hydraulic conductivity, and storage coefficient parameters.

First consider source-sink components. For convenience, the source and sink terms are grouped into three independent random variables: (1) the leakage term, which represents the flow between the confined and unconfined aquifers; (2) the net-surface flux term, which consists of percolation from precipitation, streams and canals, and the evapotranspiration rate; and (3) the pumpage term. The size of the computational problem can be considerably reduced if we assume that parameters and boundary conditions have the same coefficient of variation for each subregion used to characterize these three random variables. Thus, potentially many independent random variables reduce to three independent random variables. In other words, leakage through confining layers, net-surface flux, and pumpage terms are assumed to have the same effect on the fluctuation of the water table in each of the six subregions. The feasibility of grouping these random variables into one lumped random variable was investigated by studying three cases.

Case 1 consisted of investigating a single random variable deterministic-probabilistic model to study the individual effect of the above three random variables. Simulations were done for each random variable while holding the other variables to the mean values. Results indicated that the water table of the unconfined aquifer was sensitive to the net-surface flux term. The pumpage term had isolated effects at nodal points where pumping and artesian wells are assigned.

Case 2 consisted of investigating a three random variable deterministic-probablistic model to study the combined effect from the three random variables. The estimated variance for each nodal point was less than the sum of the variances from the three individual simulations in Case 1. That there is a difference is not surprising because the relation between the three random variables and the water table model, (6), is nonlinear.

Case 3 consisted of investigating a perfect correlation between each pair of random variables. The simulated mean water table and its standard deviation had about the same results as Case 2, indicating that the leakage term, the net-surface flux, and the pumpage terms can be considered as three perfectly correlated random variables rather than three independent random variables. In other words, one can mathematically consider the three random variables as a single random variable in the proposed deterministic-probabilistic model.

Similar to the above study, regional grouping of hydraulic conductivity was studied. The saturated hydraulic conductivity for the unconfined aquifer and transmissivity for the confined aquifer were grouped into three random variables: (1) volcanic areas, (2) bedrock, fault zone, and lakebed areas, and (3) upslope and valley floor areas. An optimistic 50-percent coefficient of variation for each random variable was assumed for purposes of several studied cases.

The results indicate that the saturated hydraulic conductivity variable for the upslope and valley floor areas is more sensitive than the hydraulic conductivity for the other two areas. It is concluded that hydraulic conductivities and transmissivities have the same overall effects on the fluctuation of the water table although this effect is more pronounced in the upslope and valley floor areas. Because valley floor areas are of primary concern, considering hydraulic conductivity as an independent random variable with similar valley-wide characteristics is conservative.

The specific yields of the unconfined aquifer and the storage coefficients of the confined aquifer were grouped into three random variables in the same way as the saturated hydraulic conductivities and the transmissivities. Assuming a 20-percent coefficient of variation for each random variable, a similar analysis as described above indicates that all specific yields and the storage coefficients have the same overall effects on the fluctuation of the water table.

The foregoing sensitivity analyses indicates reducing the original eight independent random variables to three general random variables: (1) the net-surface flux term, which includes all source and sink terms; (2) the conductivity term, which includes all saturated hydraulic conductivity and transmissivity terms; and (3) the storage term, which includes the specific yield and storage coefficient terms.

To apply (7), Yen and Guymon [1988] demonstrate that small coefficients of variation are required for uncertain variables. Somewhat optimistic coefficients of variations are used in this study: 20 percent for the lumped net-surface flux term, 20 percent for storage terms, and 50 percent for conductivity terms. Individual terms of the lumped net-surface flux term, for example, evapotranspiration and deep percolation, probably have a coefficient of variation that is higher considering the sparse data for which distributed estimates are made. The combined terms may have a lower (or possibly higher) coefficient of variation. The assumed coefficient of variation for hydraulic conductivity is certainly optimistic. Carefully controlled experiments have demonstrated a high coefficient of variation for saturated hydraulic conductivity. Should large coefficients of variation be required, the only option is to use Monte Carlo simulation method.

Although not attempted in this study, application of geostatistical methods (such as Kriging) and inverse methods to this problem would have substantiated the assumed coefficients of variation used. Although not yet well developed for dynamic simulation of ground-water flow, these approaches, if applied to the steady-state case considered above, would have yielded valuable information on uncertainty that could increase the confidence of uncertain statistics applied to this study.

The deterministic-probabilistic model was applied to both the steady-state and dynamic cases described above. Parameters discussed above were used in both simulations.

Figure 8 presents simulated steady-state results of the estimate of the mean water-table elevations for the unconfined aquifer. The simulated mean water table closely approximated the measured water table for assumed steady-state conditions. Figure 9 presents the standard deviation for the simulated mean steady-state conditions. The estimated standard deviation of the simulated water table for much of the basin is less than 0.3 m, indicating a highly satisfactory modeling result. In the area near Tinemaha Reservoir, estimated standard deviations are higher, which can be attributed to the substantial uncertainty associated with modeled flow through the volcanic deposits. Between Independence and Lone Pine, substantially higher standard deviations were estimated (about 1.3 m). This area is the main area where pumping of the deep confined aquifer occurs. Errors in the confining layer leakage factor or the error in assuming horizontal flow in the model introduce significant modeling errors.

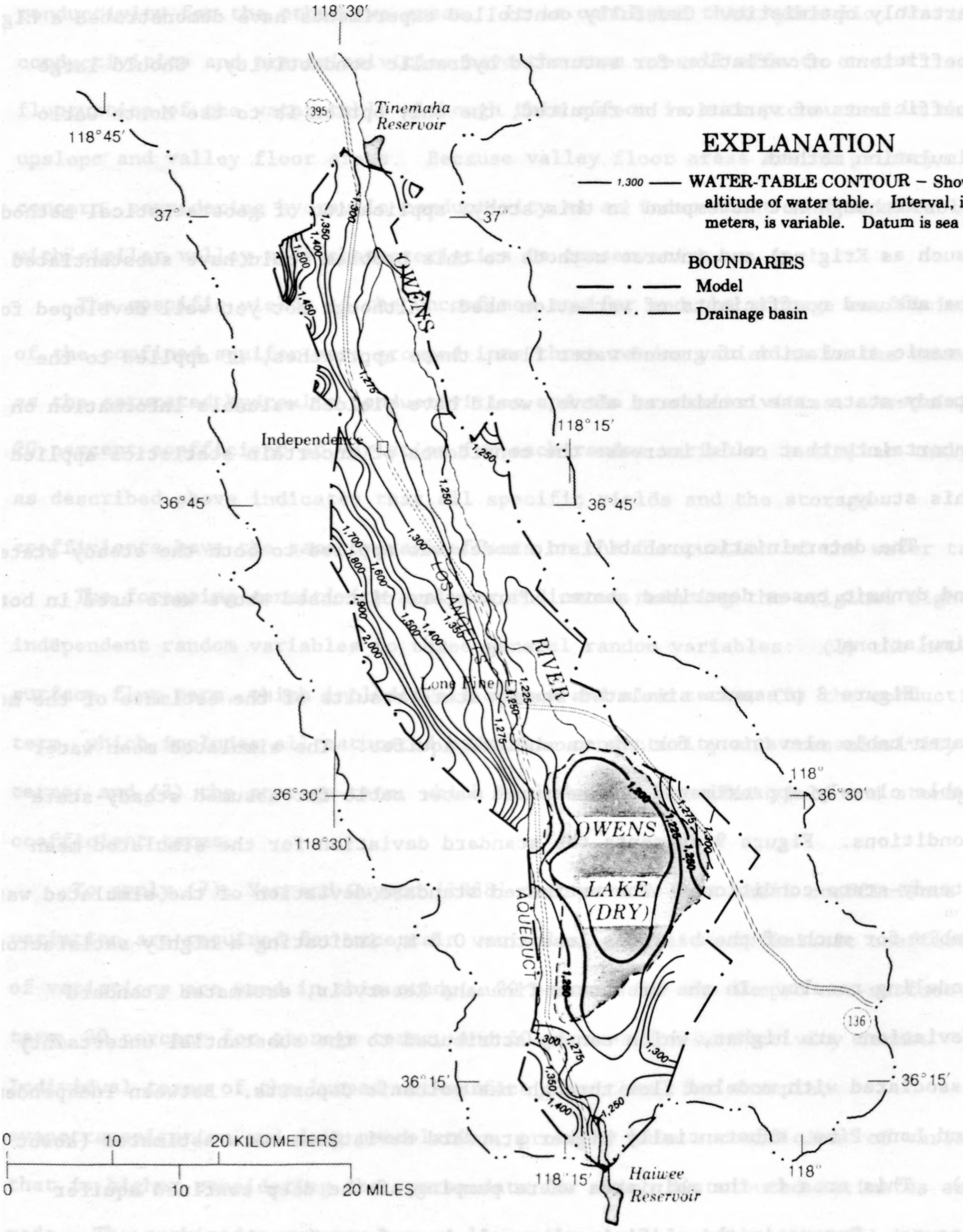

FIGURE 8.—Simulated steady-state results of the mean water-table elevations for the unconfined aquifer.

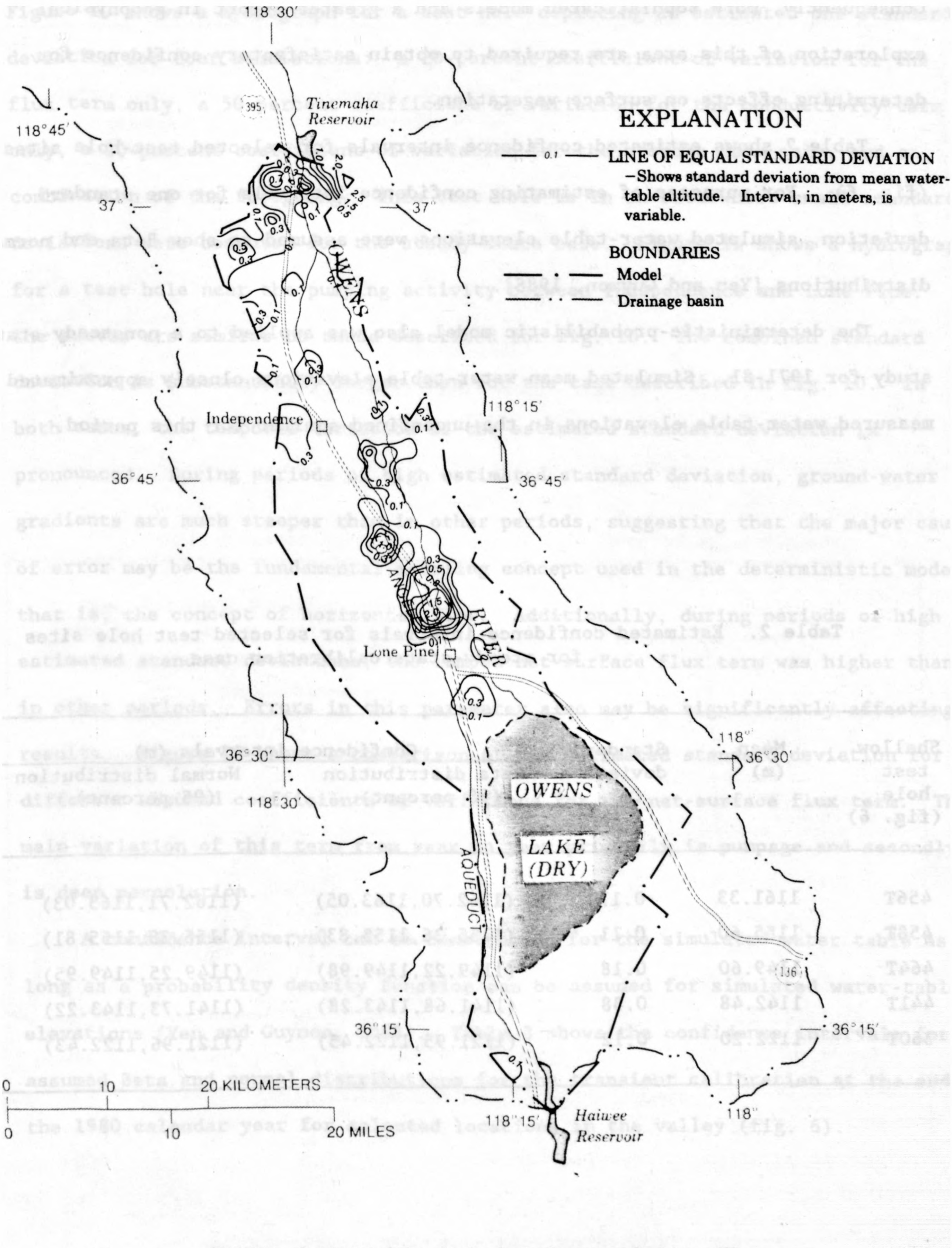

FIGURE 9.—Standard deviations for the simulated mean steady-state conditions.

Consequently, more sophisticated models and a greater effort in geophysical exploration of this area are required to obtain satisfactory confidence for determining effects on surface vegetation.

Table 2 shows estimated confidence intervals for selected test-hole sites (fig. 6). For purposes of estimating confidence intervals for one standard deviation, simulated water-table elevations were assumed to show Beta and normal distributions [Yen and Guymon, 1988].

The deterministic-probabilistic model also was applied to a nonsteady-state study for 1971-81. Simulated mean water-table elevations closely approximated measured water-table elevations in the unconfined aquifer for this period.

Table 2. Estimated confidence intervals for selected test hole sites for steady-state calibration case

Shallow test hole (fig. 6)	Mean (m)	Standard deviation (m)	Confidence intervals (m)	
			Beta distribution (98 percent)	Normal distribution (95 percent)
456T	1161.33	0.17	(1162.70,1163.05)	(1162.71,1163.03)
458T	1155.60	0.11	(1155.36,1155.83)	(1155.38,1155.81)
464T	1149.60	0.18	(1149.22,1149.98)	(1149.25,1149.95)
441T	1142.48	0.38	(1141.68,1143.28)	(1141.73,1143.22)
360T	1122.20	0.12	(1121.95,1122.45)	(1121.96,1122.43)

Figure 10 shows a hydrograph for a test hole depicting an estimated one standard deviation for four simulations: a 20-percent coefficient of variation for the flux term only, a 50-percent coefficient of variation for the conductivity term only, a 20-percent coefficient of variation for the storage term only, and a combination of the foregoing. This test hole is in an area where small standard deviations were computed for the steady-state case. Figure 11 shows a hydrograph for a test hole near the pumping activity between Independence and Lone Pine. The curves are similar to those described for fig. 10. The combined standard deviation is substantially larger than for the case described in fig. 10. In both cases, the temporal variation of the estimated standard deviation is pronounced. During periods of high estimated standard deviation, ground-water gradients are much steeper than in other periods, suggesting that the major cause of error may be the fundamental modeling concept used in the deterministic model, that is, the concept of horizontal flow. Additionally, during periods of high estimated standard deviations, the lumped net-surface flux term was higher than in other periods. Errors in this parameter also may be significantly affecting results. Figure 12 shows a comparison of the estimated standard deviation for different assumed coefficients of variations for the net-surface flux term. The main variation of this term from year to year primarily is pumpage and secondly is deep percolation.

A confidence interval can be constructed for the simulated water table as long as a probability density function can be assumed for simulated water-table elevations [Yen and Guymon, 1988]. Table 3 shows the confidence intervals for assumed Beta and normal distributions for the transient calibration at the end of the 1980 calendar year for selected locations in the valley (fig. 6).

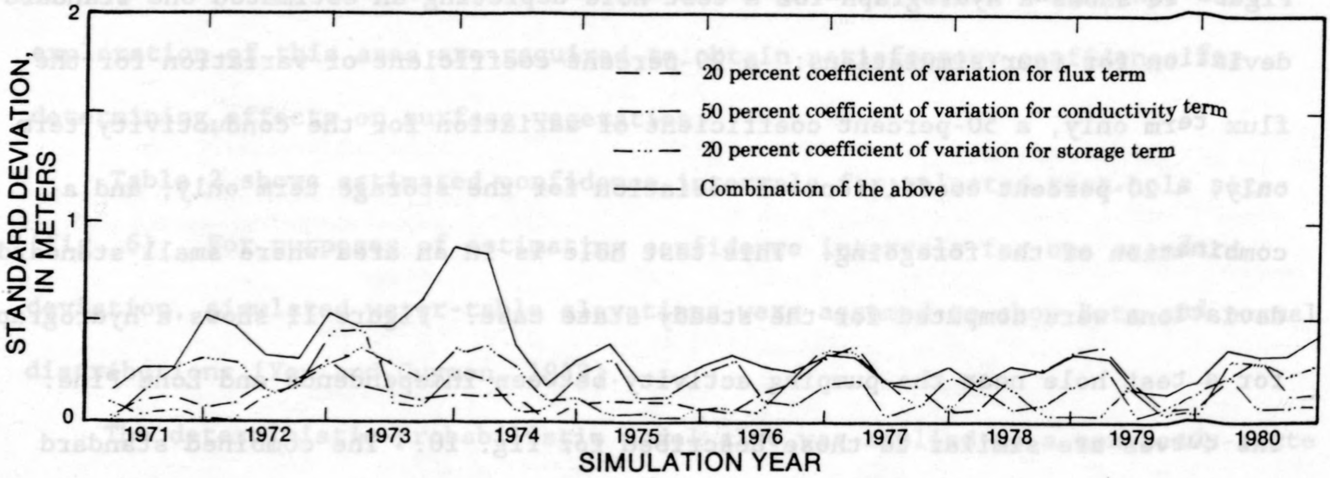

FIGURE 10.—Standard deviations for shallow test hole 456T.

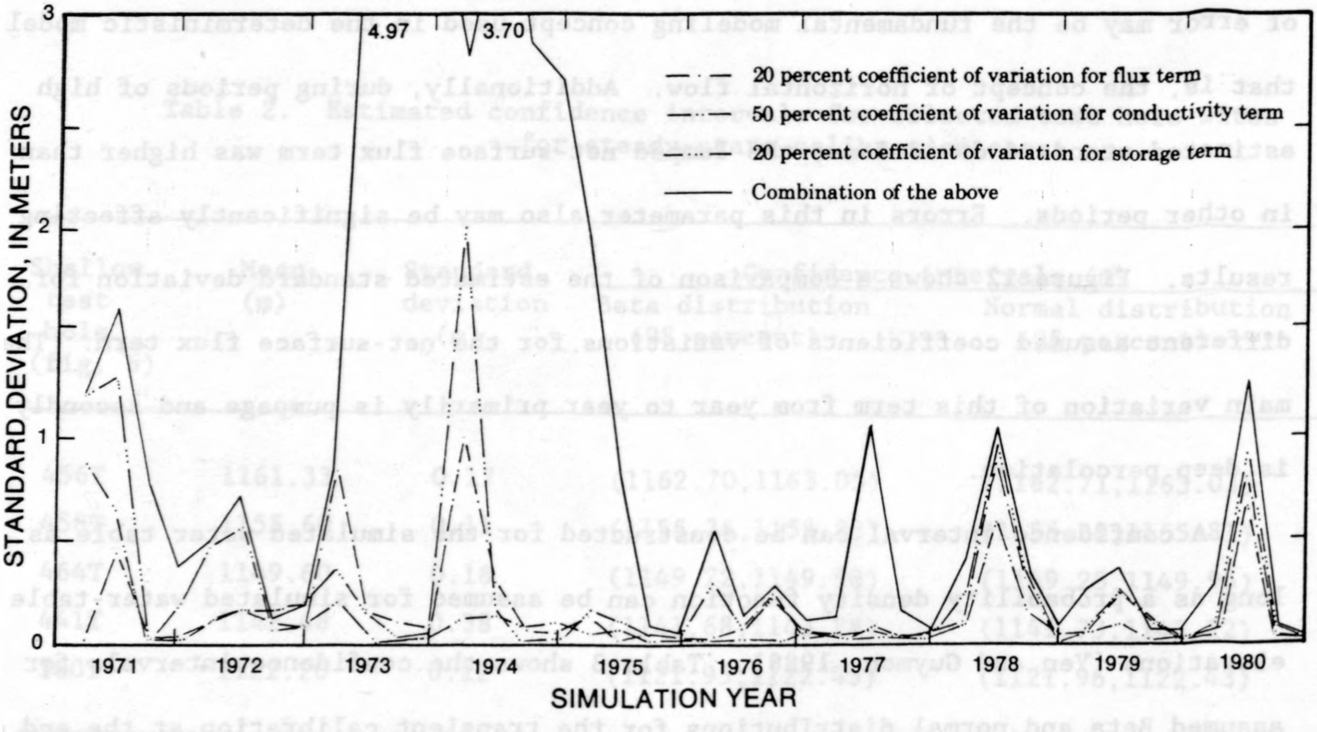

FIGURE 11.—Standard deviations for shallow test hole 441T.

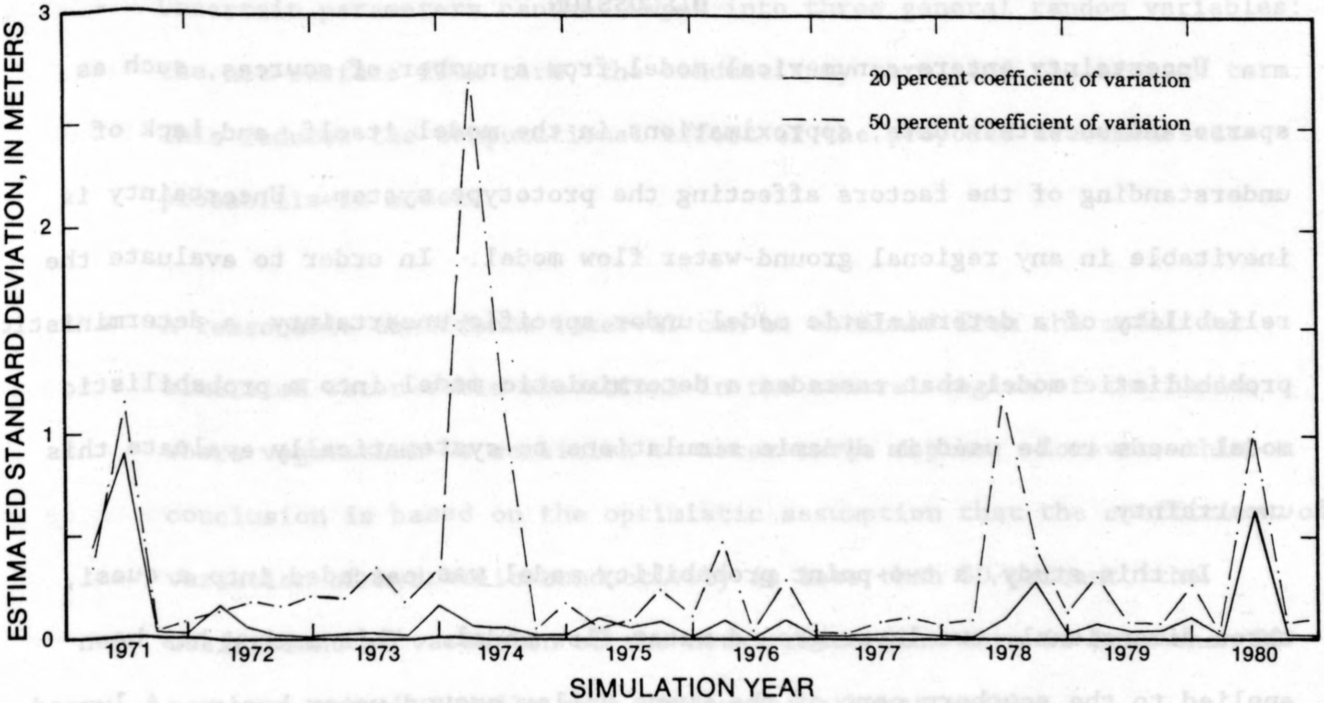

FIGURE 12.—Comparison of estimated standard deviations for different coefficients of variation for net-surface flux term for shallow test hole 458T.

Table 3. Confidence intervals of observation wells for transient calibration case at the end of 1980 calendar year

Shallow test hole (fig. 6)	Mean (m)	Standard deviation (m)	Confidence intervals (m)	
			Beta distribution (98 percent)	Normal distribution (95 percent)
507T	1157.64	0.22	(1157.19,1158.10)	(1157.19,1158.07)
455T	1162.16	3.96	(1153.85,1170.47)	(1154.40,1169.92)
456T	1161.04	0.45	(1160.10,1161.98)	(1160.16,1161.92)
458T	1156.67	0.05	(1156.57,1156.77)	(1156.57,1156.76)
464T	1150.19	0.29	(1149.57,1150.80)	(1149.61,1150.76)
411T	1156.43	2.76	(1150.71,1162.33)	(1151.01,1161.85)
364T	1189.14	1.37	(1186.26,1192.03)	(1186.45,1191.84)
441T	1144.55	0.05	(1144.46,1144.65)	(1144.47,1144.64)
400T	1142.85	0.13	(1142.59,1143.15)	(1142.60,1143.13)
360T	1133.45	1.43	(1130.46,1136.45)	(1130.66,1136.55)

DISCUSSION

Uncertainty enters a numerical model from a number of sources, such as sparse and uncertain data, approximations in the model itself, and lack of understanding of the factors affecting the prototype system. Uncertainty is inevitable in any regional ground-water flow model. In order to evaluate the reliability of a deterministic model under specific uncertainty, a deterministic-probabilistic model that cascades a deterministic model into a probabilistic model needs to be used in dynamic simulations to systematically evaluate this uncertainty.

In this study, a two-point probability model was cascaded into a quasi, three-dimensional, two-layer ground-water flow model. This method has been applied to the southern part of the Owens Valley ground-water basin. A lumped confined aquifer system was used in this study to represent a multiconfined aquifer system.

The simplified two-point estimate method is equivalent to the first-order analysis for small coefficients of variation and is comparable to the Monte Carlo simulation method [Yen and Guymon, 1988]. Prior assumptions are not required concerning the probability density functions of the uncertain parameters. Only an estimate of parameter mean and coefficient of variation are needed. The method is general and is applicable to any deterministic model. Instead of the many costly simulations required by the commonly used Monte Carlo simulation method, only 2^N (N is the number of the uncertain parameters) simulations are needed.

Specific conclusions applicable to the Owens Valley study resulting from this research are:

- Uncertain parameters can be lumped into three general random variables: the net-surface flux term, the conductivity term, and the storage term. This reduces the computational effort of the proposed deterministic-probabilistic model.

- A reasonable confidence interval can be obtained from the model for simulated water-table elevations in the central region of the basin, where vegetation is sensitive to water-table depths. However, this conclusion is based on the optimistic assumption that the coefficient of variation of hydraulic conductivity is less than 50 percent, the coefficient of variation of the net-surface flux term is less than 20 percent, and that wells that are pumped are not nearby.

- Simulated results are insensitive to uncertainty in the storage term under the assumption that the coefficient of variation is less than 20 percent.

- Large confidence intervals in simulated results are obtained from the model in the volcanic area on the northern edge of the model area, the transitional zone between the upslope area and the valley floor area, and the area adjacent to wells that are pumped.

- In volcanic areas, improved confidence intervals require detailed geologic studies and improved definition of hydraulic parameters.

- A much finer discretization for the quasi, three-dimensional modeling approach used herein or three-dimensional models are needed to increase confidence intervals in areas adjacent to wells that are pumped. In such areas, the nonlinear nature of the problem is more pronounced, and the two-point estimate method probably overestimates model errors, such as estimates of water-table elevations.

- Because evapotranspiration rates are a major factor in the lumped flux term used herein, estimates of evapotranspiration rates need to have a low coefficient of variation (perhaps less than 50 percent because of the second conclusion) to achieve an acceptable confidence interval using any modeling approach.

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