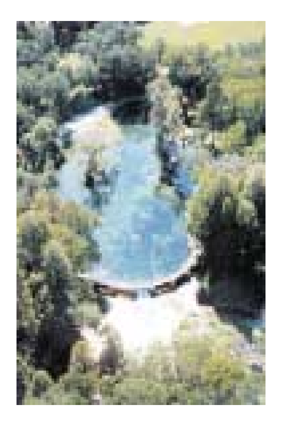
Application of Nonlinear Least-Squares Regression to Ground-Water Flow Modeling, West Central Florida



Water-Resources Investigations Report 00-4094

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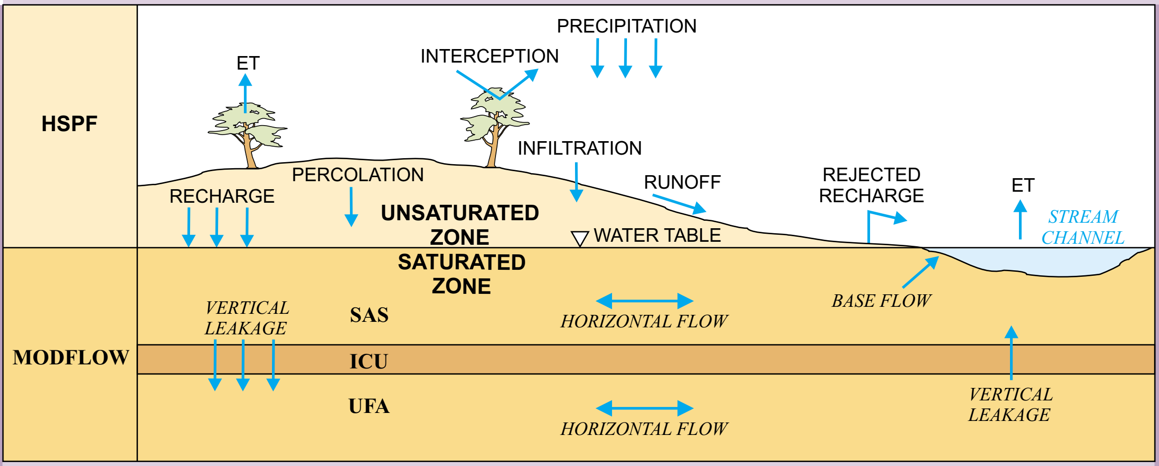

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Cover photograph: Crystal Springs
(Manny Lopez, Southwest Florida Water Management District)

Application of Nonlinear Least-Squares Regression to Ground-Water Flow Modeling, West-Central Florida

By Dann K. Yobbi

U.S. GEOLOGICAL SURVEY

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U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Suite 3015
227 N. Bronough Street
Tallahassee, FL 32301

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Application of Nonlinear Least-Squares Regression to Ground-Water Flow Modeling, West-Central Florida

By Dann K. Yobbi

Abstract

A nonlinear least-squares regression technique for estimation of ground-water flow model parameters was applied to an existing model of the regional aquifer system underlying west-central Florida. The regression technique minimizes the differences between measured and simulated water levels. Regression statistics, including parameter sensitivities and correlations, were calculated for reported parameter values in the existing model. Optimal parameter values for selected hydrologic variables of interest are estimated by nonlinear regression. Optimal estimates of parameter values are about 140 times greater than and about 0.01 times less than reported values. Independently estimating all parameters by nonlinear regression was impossible, given the existing zonation structure and number of observations, because of parameter insensitivity and correlation. Although the model yields parameter values similar to those estimated by other methods and reproduces the measured water levels reasonably accurately, a simpler parameter structure should be considered. Some possible ways of improving model calibration are to: (1) modify the defined parameter-zonation structure by omitting and/or combining parameters to be estimated; (2) carefully eliminate observation data based on evidence that they are likely to be biased; (3) collect additional water-level data; (4) assign values to insensitive parameters, and (5) estimate the most sensitive parameters first, then, using the optimized values for these parameters, estimate the entire data set.

INTRODUCTION

A variety of techniques have been used to analyze the water-supply problems in west-central Florida including the use of numerical ground-water flow models. A common use of the numerical models is to predict the response of an aquifer to planned stresses. While the mathematical and computational aspects of such response predictions are reasonably well developed, the question of confidence in parameter estimates has not been completely resolved. Model calibration is traditionally accomplished by manual trial-and-error approach during which the modeler iteratively selects parameter values to improve the model results using intuition about model response to changes in parameter values. A calibration obtained using a trial-and-error approach alone does not guarantee the statistically best solution. Consequently, there is no practical way to assess model uniqueness, if the observations support the level of model complexity, or if a simpler model would significantly improve model fit.

Model calibration can be facilitated using an inverse model (such as nonlinear least-squares regression), in which the parameter values are adjusted automatically to match field observations as closely as possible. Inverse modeling can improve the quality of ground-water models and yield results that are not readily available through trail-and-error calibration efforts (Poeter and Hill, 1996). Inverse modeling reveals data shortcomings and needs, lack of sensitivity of estimated parameters to calibration data, and extreme parameter correlation that can be easily overlooked during trial-and-error calibration. Using inverse modeling for model calibration quantifies the uncertainty in parameter estimates and statistically gives the most appropriate solution for the given input parameters.

To facilitate the routine use of the nonlinear least-squares regression method of inverse modeling, the U.S. Geological Survey (USGS) in cooperation with Tampa Bay Water and the Southwest Florida Water Management District (SWFWMD), began a study in 1997 to apply this method to the existing central northern Tampa Bay (CNTB) area hydrologic flow model. Nonlinear least-squares regression was used to determine parameter sensitivities and correlations and to estimate parameter values of the existing model.

Purpose and Scope

The purpose of this report is to describe the application of nonlinear least-squares regression to the existing ground-water flow model of the CNTB area. The study was limited to the CNTB area hydrologic model defined by SDI Environmental Services, Inc. (SDI), (1997). The ground-water flow model utilized for this study is based on the data and information presented by SDI (1997) for the CNTB area hydrologic flow model. The hydrologic and geologic setting of the study area is briefly described in subsequent sections. A short description of the CNTB area hydrologic model and regression procedure follows. The remainder of the report is devoted to parameter-estimation analysis, as it was applied to the CNTB area hydrologic model. Discussions include descriptions of modeling procedures, evaluation of parameter-value regression statistics, including parameter sensitivities and correlations for parameter values reported by SDI (1997). The optimal set of parameter values and associated statistics determined by regression is presented last.

Description of the Study Area

Detailed descriptions of the study area are presented in SDI (1997) and SWFWMD (1993). The study area encompasses approximately 2,000 square miles (mi^2) that includes all of Pasco County; most of Hernando, Pinellas and Hillsborough Counties; and part of Polk County (fig. 1). Surface topography is characterized by relatively flat, marshy lowlands along the coast, rolling hills of intermediate relief throughout the central part of Pasco County, and sand terraces to the northeast. The most prominent topographic feature of the area is the Brooksville Ridge, which is located in central Hernando and eastern Pasco Counties (fig. 2). Land surface altitudes range from sea level near the coast to over 300 feet (ft) above sea level along the Brooksville Ridge.

Several rivers (six) and their tributaries, several small streams along the coast, and some internally drained and ephemeral streams that flow only during extreme rainfall events compose the surface-water system of the study area (fig. 3). The two largest riverine systems are the Hillsborough and Withlacoochee Rivers. There are hundreds of lakes, swampy plains, and intermittent ponds dispersed throughout the study area, ranging in size from less than 1/4 acre to more than 2,500 acres. A large concentration of lakes exist in several areas, namely northwest Hillsborough County, central Pasco County, and along the Brooksville and Lakeland Ridges.

Numerous springs (17) are located in the study area and are either found inland, flowing to adjacent rivers or along the coast, discharging directly to the Gulf of Mexico (fig. 3). The two most important springs are Weeki Wachee Spring, located in western Hernando County and Crystal Springs, located along the northern reaches of the Hillsborough River. Crystal Springs provides a large portion of the Hillsborough River's base flow while Weeki Wachee Spring is the source of flow in the Weeki Wachee River.

The ground-water flow system beneath the study area is a multilayered system consisting of a thick sequence of carbonate rocks overlain by clastic deposits (fig. 4). The surficial deposits and carbonate rocks are subdivided into a hydrogeologic framework that forms a sequence of two aquifers and one confining unit. This framework includes the unconfined surficial aquifer system and the confined Floridan aquifer system. A low permeability intermediate confining unit separates the aquifers. The Floridan aquifer system consists of the Upper and Lower Floridan aquifers that are separated by a middle confining unit. The middle confining unit contains saltwater in the study area, and the freshwater flow is limited to the Upper Floridan aquifer. The Upper Floridan aquifer is underlain by low-permeablility evaporitic limestone that forms the bottom of the fresh ground-water flow system.

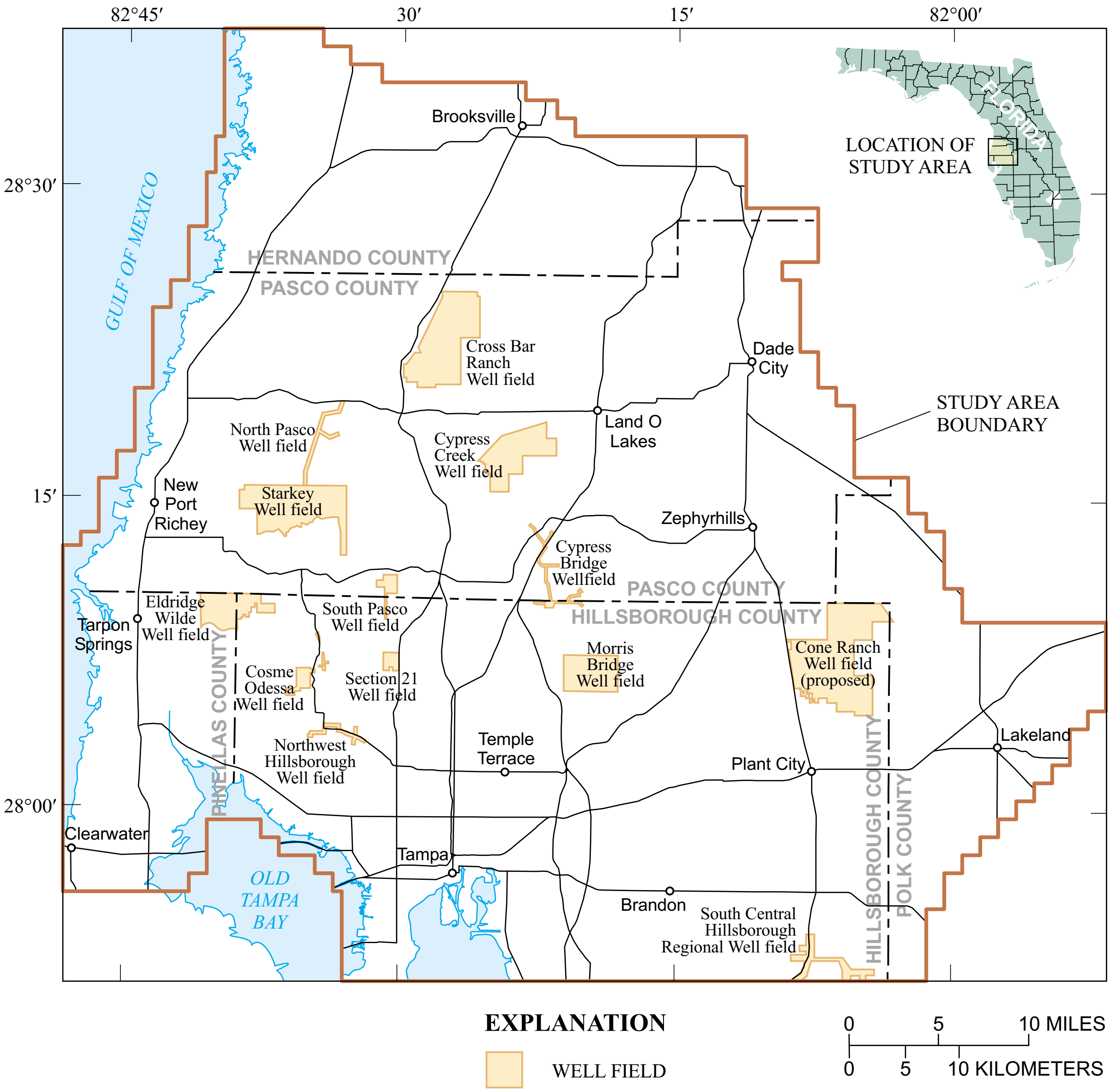


Figure 1. Location of study area and well fields.

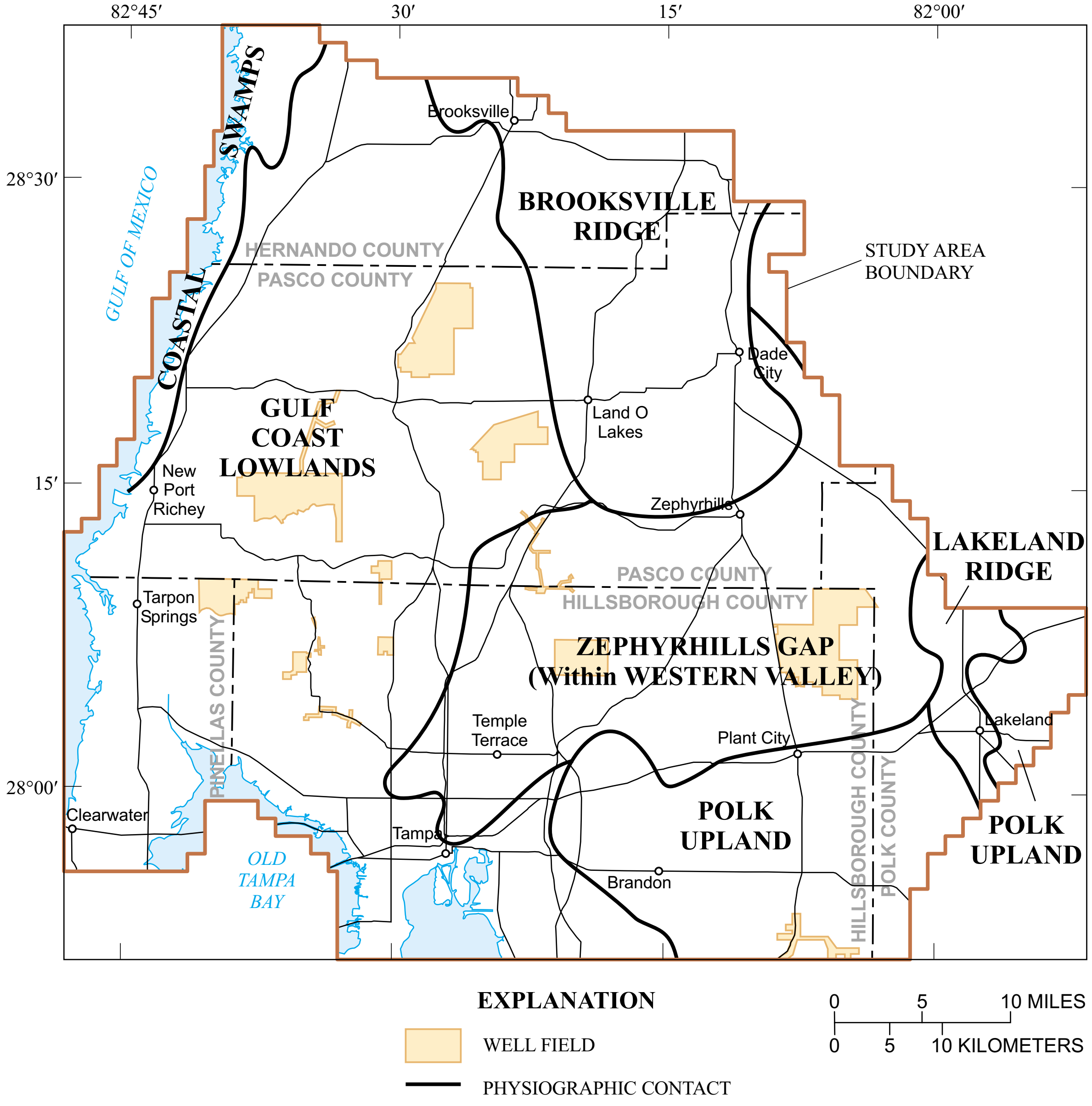


Figure 2. Physiographic provinces (modified from SDI Environmental Services, Inc., 1997).

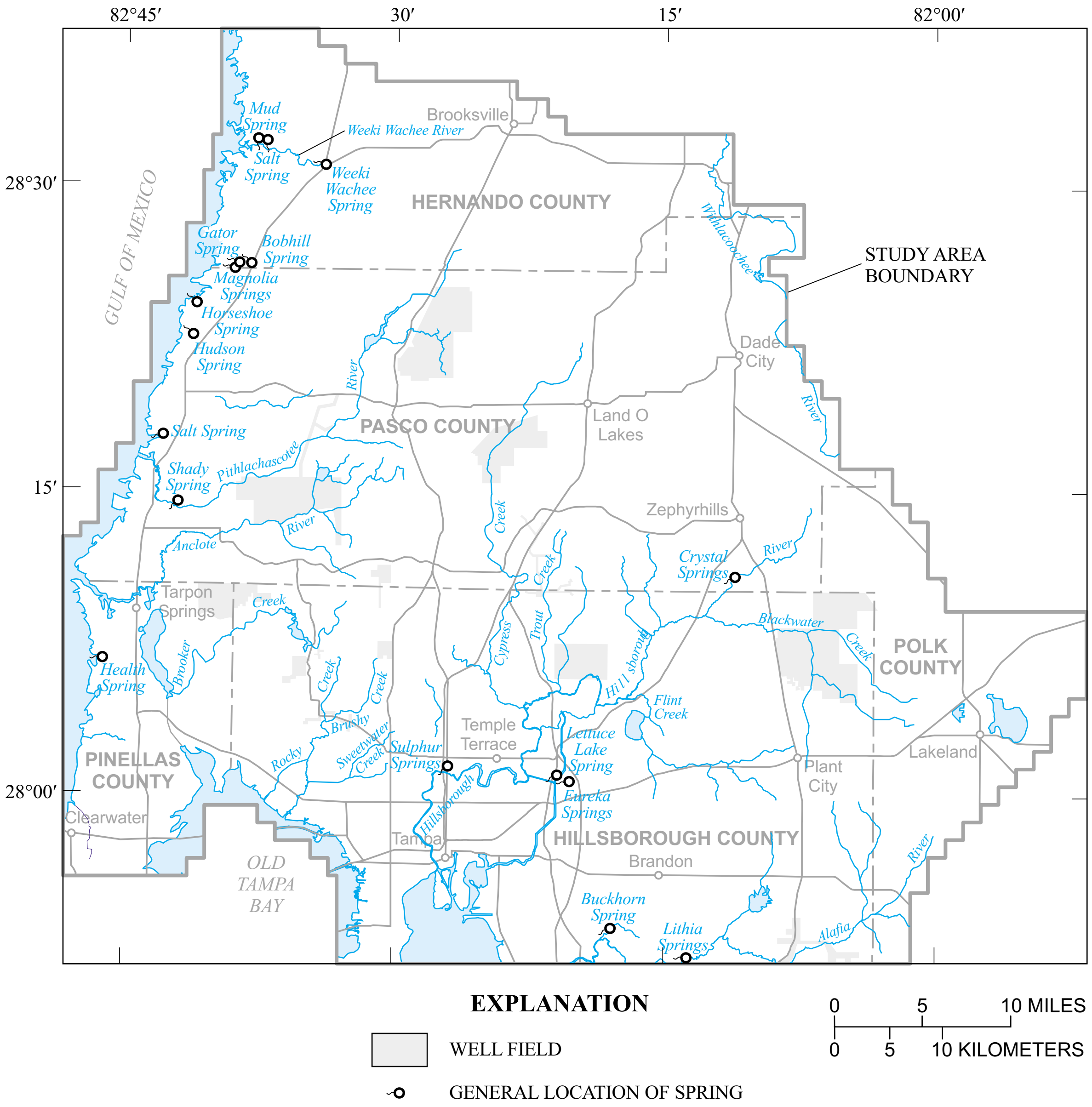


Figure 3. Location of rivers and springs.

Description of the Existing CNTB Area Hydrologic Model

The existing CNTB area hydrologic model is a coupled surface-water and ground-water flow model developed by SDI (1997) for the CNTB area. The CNTB area hydrologic flow model links together the surface-water model HSPF (Johanson and others, 1984) with the ground-water model MODFLOW (McDonald and Harbaugh, 1988) (fig. 5). HSPF simulates the basin water budget and the processes above the saturated ground-water system (precipitation, evapotranspiration, interception, surface-water withdrawal, infiltration, interflow, runoff, rejected recharge, and percolation to the ground-water system). HSPF is the tool for converting precipitation data into the quantity of water that reaches the water table as ground-water inflow (recharge) and the quantity of water that is compared directly to measured stream discharges. Recharge is defined as the amount of water that has infiltrated and percolated through the unsaturated soil zone. This water represents an outflow flux from HSPF and can be thought of as the water that reaches the water table and becomes part of the saturated flow system or ground water. MODFLOW simulates the saturated ground-water system and the processes of recharge, leakage, baseflow, and ground-water withdrawals. At times, ground water can rise above land surface during periods of high recharge. Water above land surface is either allowed to pond or is transferred from the ground-water system to the surface-water system as “rejected recharge” and is routed as basin runoff.

The primary feature of the CNTB area hydrologic model is the integrating software that provides the linkage and exchange of water between the two component models, HSPF and MODFLOW. Integrating software provides linkage between the models by reformatting the output data from one hydrologic model (HSPF) for input into the other model (MODFLOW). Exchange of water between the two models occurs in several ways. Using hourly rainfall data, HSPF calculates the weekly percolation (recharge) from the surface-water system to the ground-water system and the stages in surface-water reaches of streams. MODFLOW is then run with recharge and stream stages calculated by HSPF. MODFLOW calculates aquifer water levels and base flow to and from surface-water features. Base flow calculated by MODFLOW becomes input to HSPF and stages are adjusted. The

System	Series	Stratigraphic unit		Major lithologic unit	Hydrogeologic unit	
Quaternary	Holocene and Pleistocene	Surficial sand, terrace sand, phosphorite		Sand	Surficial aquifer system	
Tertiary	Pliocene	Undifferentiated deposits		Sand, clay, and limestone	Intermediate confining unit	Upper confining unit
	Miocene	Hawthorn Group	Peace River Formation			“Water-bearing units”
			Arcadia Formation			
			Tampa Member	Limestone		Lower confining unit
	Oligocene	Suwannee Limestone			Florida aquifer system	Upper Floridan aquifer
	Eocene	Ocala Limestone				
		Avon Park Formation		Limestone and dolomite		Middle confining unit
	Paleocene	Oldsmar and Cedar Key Formation		Dolomite and limestone		Lower Floridan aquifer

Figure 4. Generalized stratigraphic and hydrogeologic section, west-central Florida.

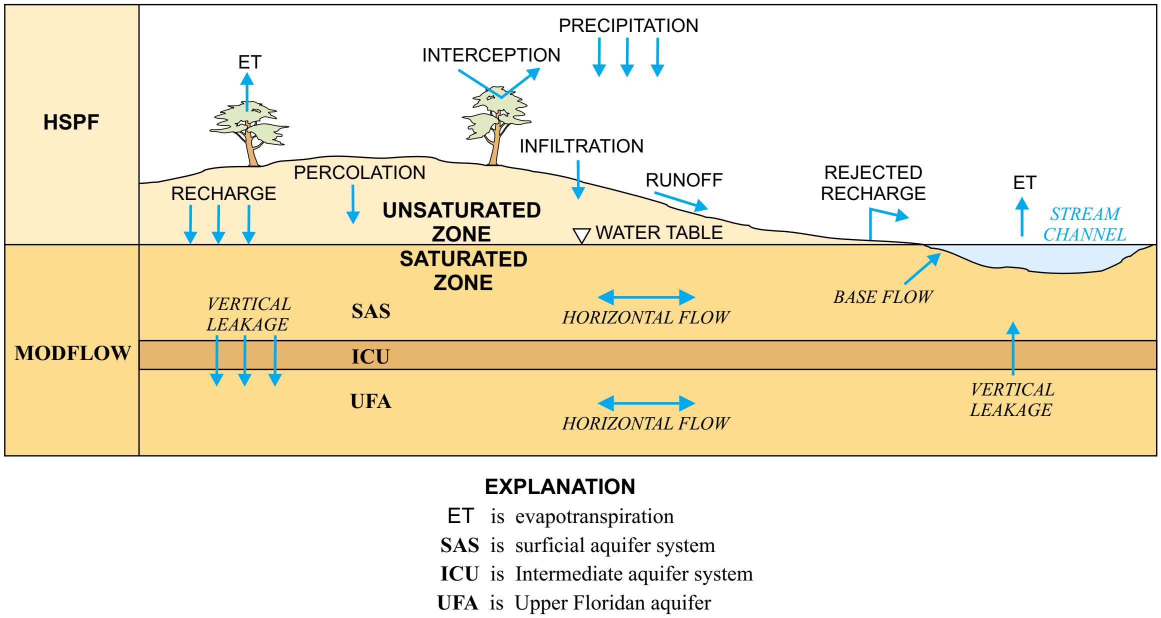


Figure 5. Primary components of the surface-water system simulated by HSPF and the ground-water system simulated by MODFLOW.

corresponding subbasin and reach numbers from HSPF to individual cells in MODFLOW are linked in the CNTB model using a Geographic Information System (GIS). The integrating software translates HSPF results (hourly increments) into stress periods used by MODFLOW (weekly), and MODFLOW results are partitioned into appropriate periods for HSPF.

Areally, the CNTB area hydrologic model is divided into a grid of 131 rows by 121 columns, with 0.25 mi^2 cells in the center of the model and cells up to 1 mi^2 elsewhere (fig. 6). The ground-water part of the CNTB area hydrologic model consists of two layers. The upper layer (layer 1) represents the surficial aquifer system as an unconfined layer. The lower layer (layer 2) represents the Upper Floridan aquifer as a confined/unconfined layer. Vertical leakage through the intermediate confining unit was simulated implicitly using a leakance array. Assigning a high leakance value (0.35 day^{-1}) simulates the absence of the confining unit. When using this leakance value, simulated water levels in model layers 1 and 2 are equal. Rivers are modeled as river cells in layer 1 and, in those locations where rivers are believed to be in direct hydraulic connection with the Upper Floridan aquifer, in model layer 2 (figs. 7 and 8). Five lakes (Stemper Lake, Bell Lake, Big Fish Lake, Crews Lake, and King Lake East) were represented as individual reaches and were simulated directly in HSPF (fig. 7). Other lakes were considered to be “windows” in the surficial aquifer system through which the water table can be observed and were assumed to behave in the same way as the surficial aquifer system. Wetlands are modeled as river cells in layer 1. Springs are represented by one or more drain cells in model layer 2. Several boundary conditions were used to constrain the lateral extent of the simulated flow system. Based on regional groundwater flow, most of the lateral extent in layer 1 is a no-flow boundary, except where the boundary coincides with the coastline of the Gulf of Mexico and Tampa Bay, which are represented in the model as specified heads. In layer 2, the southeastern and most of the northern boundaries are no flow boundaries representing flow lines in the Upper Floridan aquifer. A part of the northern boundary is represented by a general head boundary. The extreme eastern edge of the model is represented as a specified head boundary. The coastline is represented as a no-flow boundary.

The CNTB area hydrologic model was developed as a numerical tool to assess hydrologic issues related to resource/well field management and water-use permit renewal applications for the Cypress Bridge, Cypress Creek, and Cross Bar Ranch well fields (fig. 1). The simulation period is from 1971 to 1993 (approximately 1,200 weeks). The calibration period was the 12-yr period from 1976 through 1987. Simulation of the 5-yr period from 1971 through 1975 prior to calibration was used to stabilize water levels and flows in the model. The 6-yr period from 1988 through 1993, following the calibration period, was chosen as the model verification period.

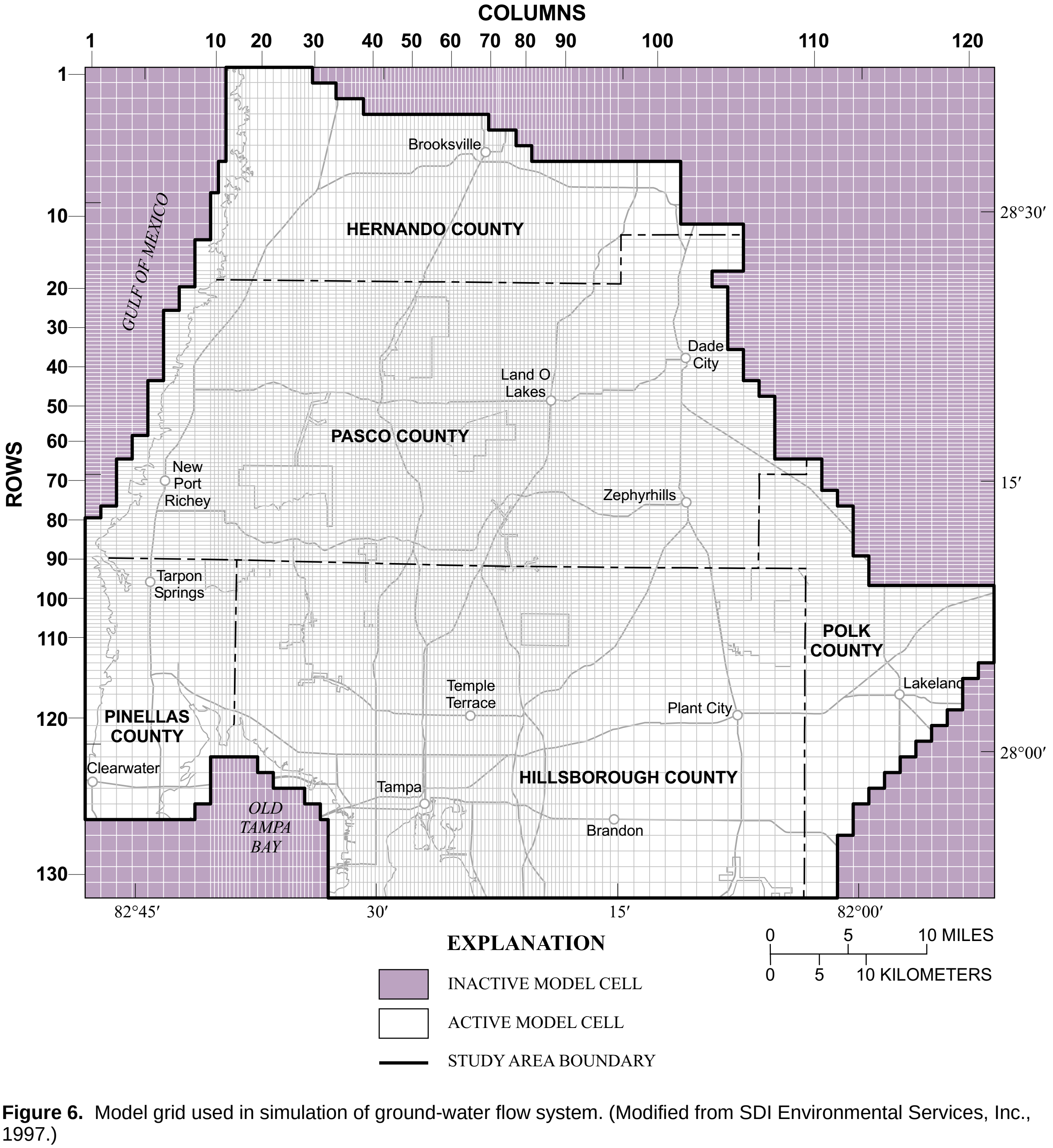


Figure 6. Model grid used in simulation of ground-water flow system. (Modified from SDI Environmental Services, Inc., 1997.)

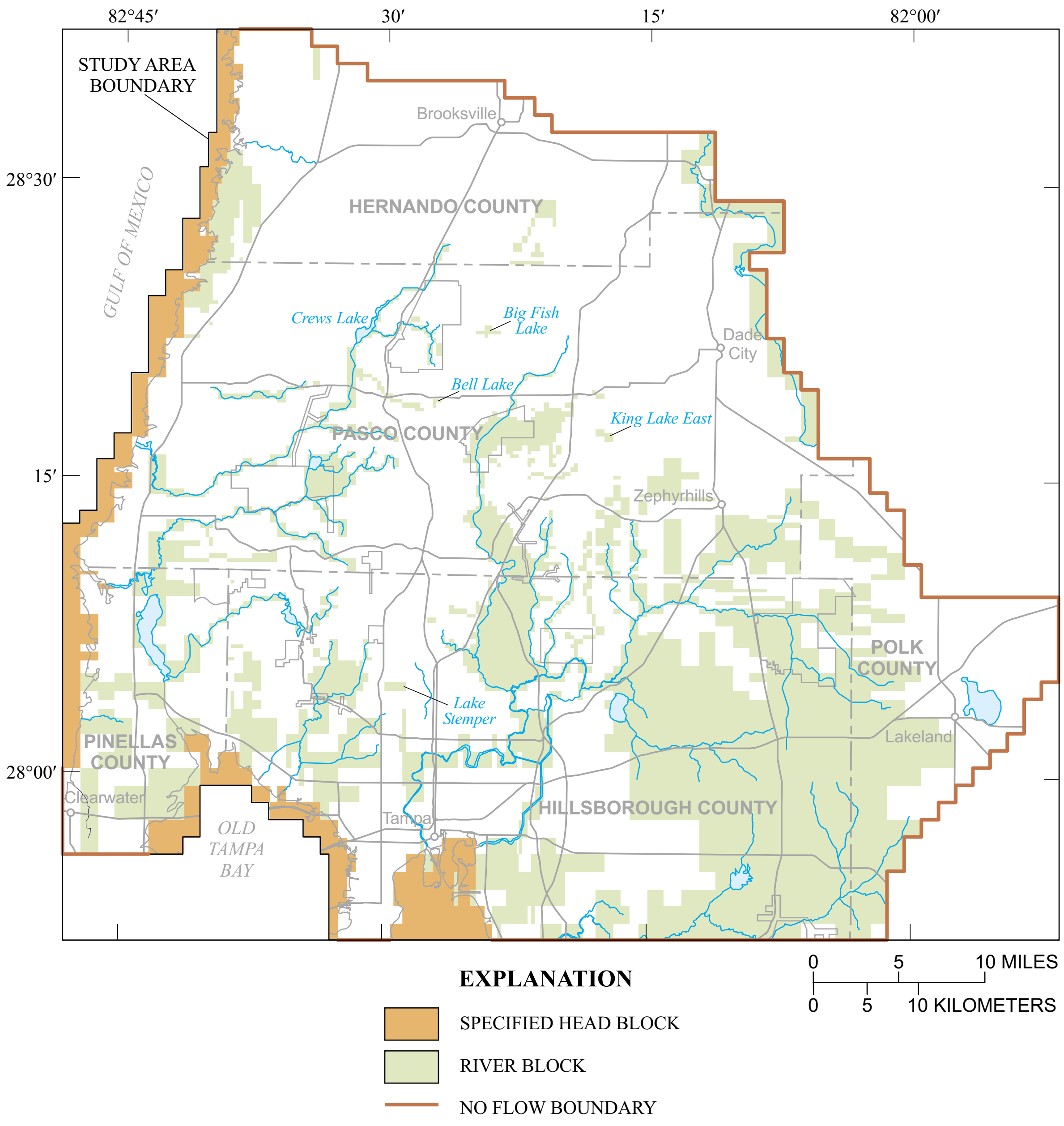


Figure 7. Model boundary conditions for the surficial aquifer system (layer 1). (Modified from SDI Environmental Services, Inc., 1997.)

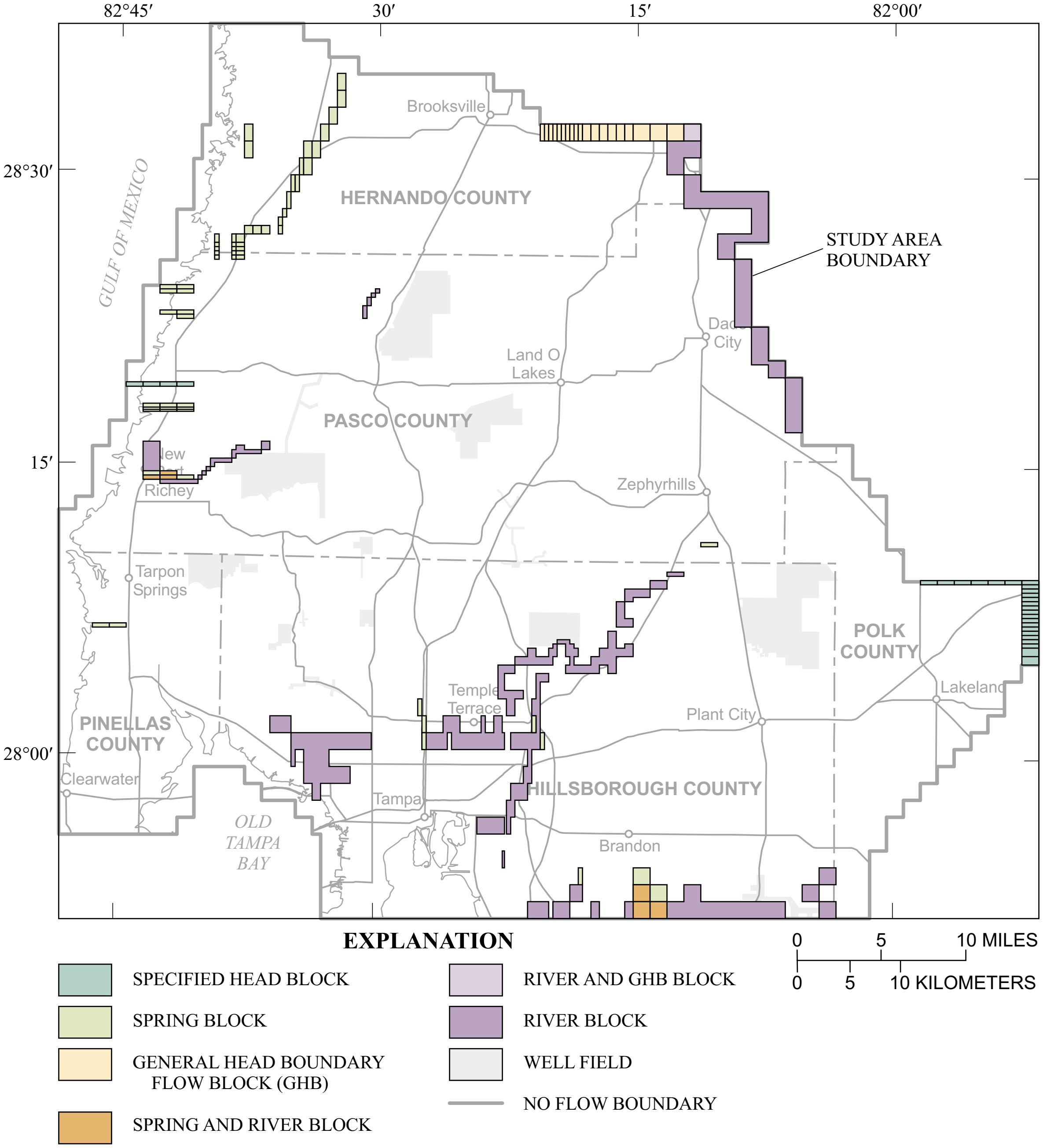


Figure 8. Model boundary conditions for the Upper Floridan aquifer (layer 2). (Modified from SDI Environmental Services, Inc., 1997.)

A generalized conceptual model of the components of the CNTB area hydrologic model is shown schematically in figure 9. The surface-water system extends to the saturated zone of the ground-water system (water table in the surficial aquifer system) and the components include rainfall, runoff, infiltration, percolation, evapotranspiration (ET), and streamflow. The ground-water components include recharge, ground-water pumpage, stream baseflow, lateral ground-water flow, and leakage between the surficial aquifer system and the Upper Floridan aquifer. Rainfall enters the soil layer of the unsaturated zone (modeled by HSPF) through infiltration. Water enters the saturated zone (modeled by MODFLOW) from the surface-water component through percolation. Water above land surface that is not allowed to pond (rejected recharge) is treated as excess water and routed as basin runoff to lateral surface-water flow. Rainfall either runs off or percolates downward and recharges the surficial aquifer system. In the surficial aquifer system, water may move laterally to discharge where it intersects land surface, be lost as ET, or leak downward to the Upper Floridan aquifer. Water in the Upper Floridan aquifer moves laterally to lowland discharge areas such as the Gulf coast where it leaks upward.

Figure 9 summarizes the annual average hydrologic budget for the CNTB model area for the 1971-93 simulation period. The simulated inflows and outflows illustrate the primary processes used to represent the surface-water system and the ground-water system in the CNTB area hydrologic model. In the simulated budget, about 75 percent of rainfall is lost to ET, 11 percent runs off, 5 percent is discharge to streams, 3 percent is discharge to springs, 2 percent leaves the area as lateral ground-water outflow, and 4 percent is pumped from the ground-water system.

Recharge to the ground-water system averages 9.6 in/yr. Part of the rainfall (2.0 in/yr) is rejected as recharge and contributes to additional ET and surface runoff. Simulated net leakage between the surficial aquifer system and the Upper Floridan aquifer was 6.8 in/yr downward, which represented 50 percent of the total flow in the surficial aquifer system. This is in agreement with high leakance characteristics of the intermediate confining unit. Consequently, hydrologic conditions in the surficial aquifer system can substantially effect conditions in the Upper Floridan aquifer. Likewise, hydrologic conditions in the Upper Floridan aquifer can substantially effect conditions in the surficial aquifer system.

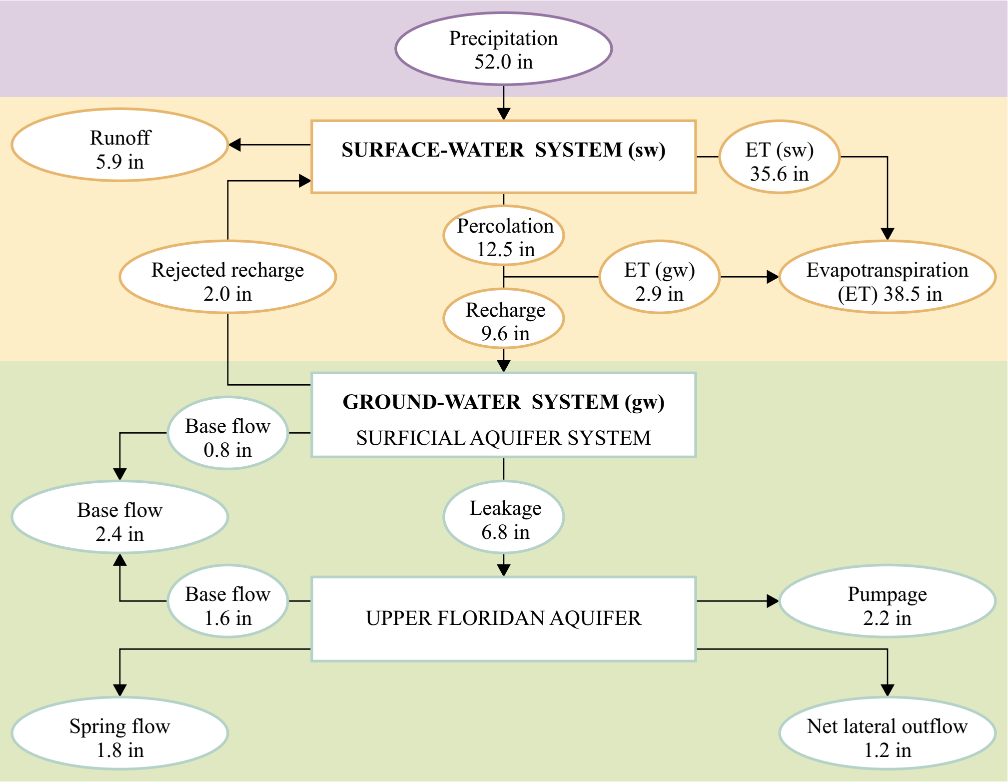


Figure 9. Simulated annual average hydrologic budget for the central northern Tampa Bay area hydrologic model 1971-93. (Modified from SDI Environmental Services, Inc., 1997).

APPLICATION OF NONLINEAR LEAST-SQUARES REGRESSION TO GROUND-WATER FLOW MODELING

Fundamentally, the process of model calibration is the same using either inverse models or the trial-and-error approach: parameter values and other aspects of the model are adjusted until the dependent variables (water levels and flows) match field observations. Important advantages of using nonlinear least-squares regression, however, are the ability to determine parameter values that produce the best match to field observations and the ability to quantify the quality of model calibration using statistical measures. The statistical framework of this process can be used to determine strengths and weaknesses of the model, the likely accuracy of simulated results, and measures of parameter uncertainty. In addition, results can be used to help evaluate whether model parameter estimates are reliably calculated with available data and what additional data could be most useful in improving the model (Poeter and Hill, 1996). Consequently, inverse modeling can improve the quality of ground-water models and yield results that are not readily available through trial-and-error calibration efforts. Also, if the inverse model converges, the model is likely to be a unique set of parameter values.

Ground-water flow is simulated using the USGS MODFLOW model (McDonald and Harbaugh, 1988). To perform inverse modeling, the flow model is linked with a nonlinear least-squares regression routine (Halford, 1992). The combined ground-water flow model and nonlinear regression is called MODOPTIM. MODOPTIM was used to: (1) identify sensitivity of water-level data to the estimation of each parameter, (2) identify parameters that are highly correlated, and (3) indicate optimal parameter values for available water-level data.

Nonlinear Least-Squares Regression Method

The nonlinear weighted least-squares regression method minimizes the sum-of-squared residuals (SS) between measured and simulated quantities and is based on a modified Gauss-Newton method (Gill and others, 1981). The SS is defined as:

$$SS = \sum_{j=1}^{n} [w_i(h_{js} - h_{jm})]^2 \quad , \qquad (1)$$

where

h_{js} is the jth simulated water level, in feet;
h_{jm} is the jth measured water level, in feet;
w_i is the weighting factor, and
n is the number of water-level comparisons.

Water levels were assigned a weighting factor of 1.0 as there was little basis for differentiating among measurements. Stream discharge measurements were not formally used during regression analysis because of difficulties of accurately determining the ground-water component of total gaged stream discharge. Spring flow also was not formally used during regression analysis because the conductance term is poorly known and because many springs are assigned to multiple grid cells.

Although the SS serves as the objective function (measure of model fit), root-mean-square error (RMSE) is reported instead because RMSE is more directly comparable to actual values and serves as a composite of the average and the standard deviation of a set (Halford, 1997). RMSE is related to the SS by:

$$RMSE = (SS/n)^{0.5} . \qquad (2)$$

The first step in the parameter-estimation process is to perform one execution of the model to establish the initial differences (residuals) between simulated and measured water levels. The residuals are squared and summed to produce the sum-of-squared residuals objective function (eq. 1), which is used by the regression to measure model fit to the observations. In the next step, the sensitivity coefficients (derivatives of simulated water-level change with respect to parameter change) are calculated by the influence coefficient method (Yeh, 1986) using the initial model results. After the residuals and the sensitivities are calculated, a single parameter-estimation iteration is performed. The current arrays of sensitivity coefficients and residuals are used by a quasi-Newton procedure (Gill and others, 1981. p. 137) to compute the parameter change that should improve the model. The model is updated to reflect the latest parameter estimates and a new set of residuals is calculated. The entire process of changing a parameter in the model, calculating new residuals, and computing a new value for the parameter is continued iteratively until model error or model-error change is reduced to a specified level or until a specified number of iterations is made (Halford, 1992). Logs of the parameters are estimated because log-parameters are better behaved from a numerical perspective, and because logs of the parameters prevent the actual parameter values from becoming negative.

Simulation Model

The CNTB area hydrologic model developed by SDI (1997) was used in this study with three modifications. First, the CNTB area hydrologic model was decoupled to run without HSPF. Second, rejected recharge simulated in the CNTB area hydrologic model (fig. 10) is simulated in this model by drains, where the elevation of the drain is set at land surface. Third, steady-state model simulations were used for the parameter estimation part of this study. Steady-state analysis assumes that ground-water levels, hydraulic gradients, and the velocity distribution of ground-water flow do not change with time. Although ground-water levels fluctuate seasonally, the annual range fluctuates around long-term averages, and therefore, the state of the aquifer system approximates a dynamic equilibrium. Time-averaged hydrologic conditions for the 1987 calendar year were chosen for steady-state conditions and parameter estimation. The

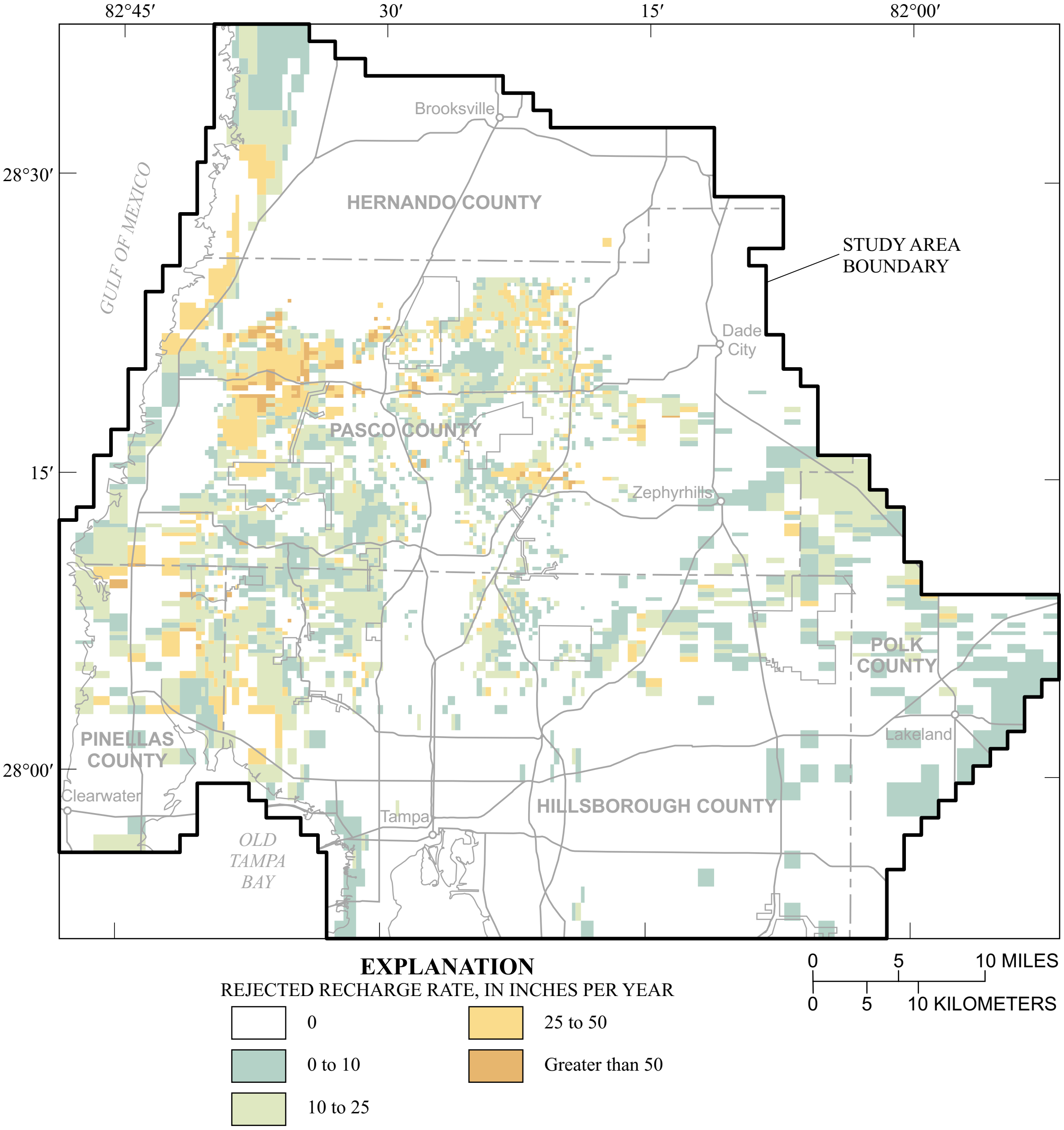


Figure 10. Areal distribution of simulated rejected recharge from the surficial aquifer system, calendar year 1987.

average 1987 hydrologic conditions were considered suitable for several reasons.

1. The frequency of data collection was sufficient for calculation of representative annual average values.
2. Measured annual precipitation in 1987 was close to the long-term average value.
3. The small net change in water levels measured in wells indicates that the change in storage in the aquifer systems was small during 1987.

Data input were obtained directly or indirectly from the CNTB area hydrologic model (SDI, 1997) and included: starting water-level values, hydraulic conductivity, bottom altitude of the surficial aquifer system, riverbed conductance values, intermediate aquifer system leakance, transmissivity of the Upper Floridan aquifer, horizontal anisotropy values of the Upper Floridan aquifer, boundary heads and boundary conductance values for the Upper Floridan aquifer, pumping rates, and drain altitudes and conductances for the surficial aquifer system and the Upper Floridan aquifer. Input data arrays also included specified recharge and discharge rates to/from the surficial aquifer system (fig. 11). Net recharge rates are calculated by substracting ET from recharge in each model cell, thus in cells where ET exceeds recharge, a negative value of recharge is obtained.

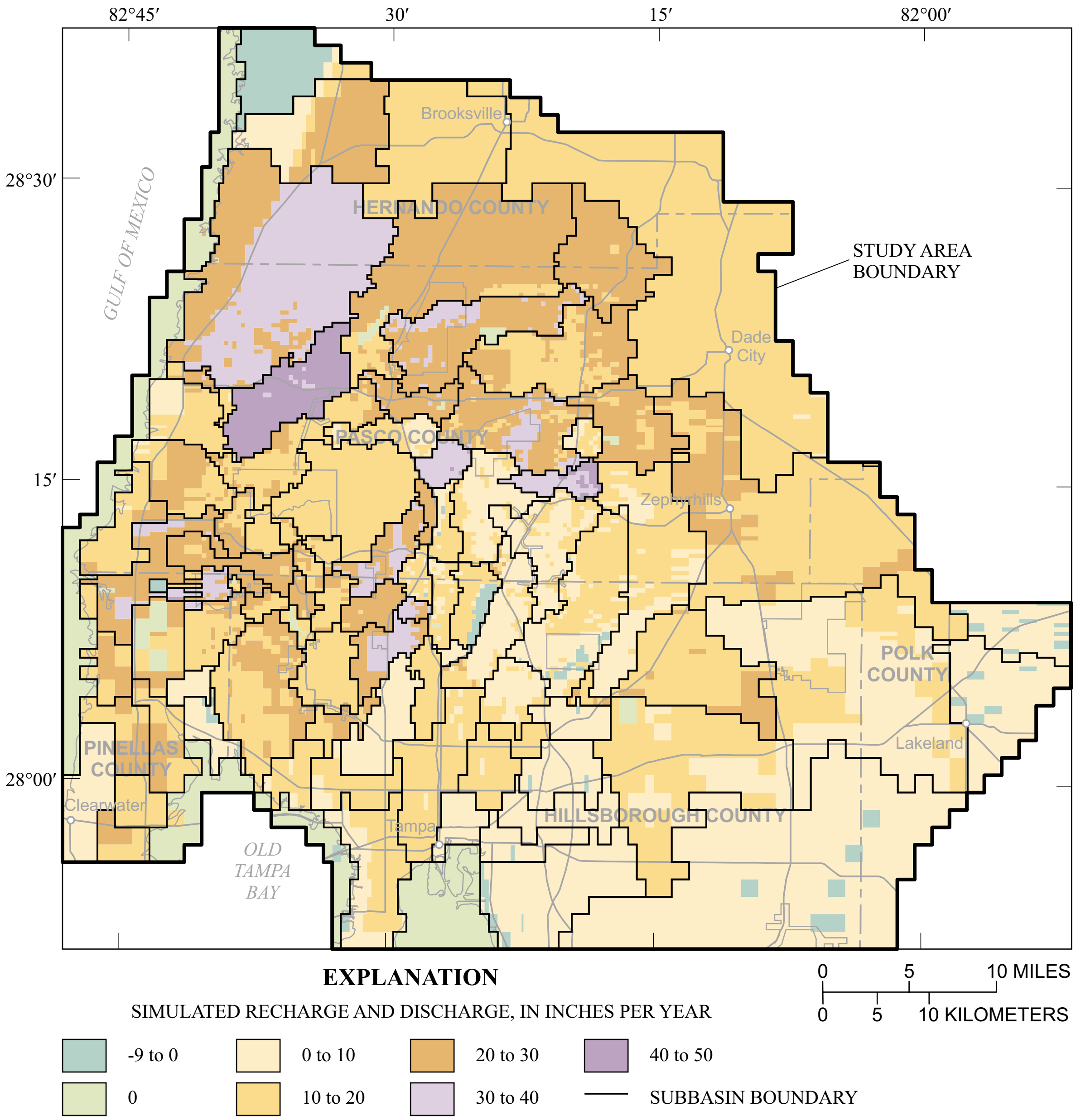


Figure 11. Simulated percolation (recharge) rates from the surface-water system to the ground-water system, calender year 1987. (Modified from SDI Environmental Services, Inc., 1997).

Observation Data

Water levels measured in 223 surficial aquifer system wells and 326 Upper Floridan aquifer wells in 1987 are the observation data used for comparison during the simulation modeling; whereas only 119 observations were used in the SDI (1997) simulation modeling. Measured water levels were used by MODOPTIM during parameter estimation to provide values to define the objective function for the model simulation. Because all water levels from wells in wellfield areas were used, the SS may be slightly biased toward these areas. As previously indicated, base flow values were not matched by parameter estimation due to difficulties of accurately determining the base flow (ground-water discharge) component of total streamflow. Spring flow values also were not matched by the regression because the conductance term is poorly known, because many individual springs were simulated with multiple grid cells, and because of the lack of accurate altitude control on spring pool elevation (altitudes of most springs were determined from topographic maps).

For each water-level observation, the following quantities were specified: measured water-level value, well location, and model layer number. Because measured water levels rarely coincide with the center of a cell, simulated water levels were interpolated laterally to points of measurements from the surrounding cells. Simulated water levels can be laterally interpolated because they are assumed to be part of a continuous distribution. Vertical interpolation of water levels was not performed because each aquifer was modeled as a single layer and the generally low permeability of the intermediate confining unit results in a discontinuity in vertical head distributions.

Parameter Structure

Simplification of the subsurface framework is inherent in the modeling process because of the required spatial discretization. Each finite-difference cell is assigned one value for each hydraulic parameter, which represents a spatially averaged uniform value. To minimize nonuniqueness problems caused by trying to estimate too many parameters, the spatial distribution of parameters is represented in MODOPTIM by dividing the model domain into zones with homogenous hydrologic properties (each zone characterized by one constant value). The zones and corresponding parameter values are defined as the "parameter structure" (figs. 12-16).

The parameter structure for the existing CNTB area hydrologic model (SDI, 1997) consists of five parameters divided into 200 parameter zones. The parameters examined in this study are (1) recharge (Qre), (2) hydraulic conductivity (K) of the surficial aquifer system, (3) leakance (L) of the intermediate confining unit, (4) transmissivity (T) of the Upper Floridan aquifer, and (5) horizontal anisotropy ratio (Kx/Ky) of the Upper Floridan aquifer.

Model Analysis

Analysis of the existing CNTB area hydrologic model consisted of two simulation phases. The goal of the first phase of model analysis was to statistically evaluate the parameter structure reported by SDI (1997). Parameter value regression statistics, including sensitivities and correlations, were calculated for the SDI (1997) calibration values by executing only one parameter-estimation iteration. The goal of the second phase of model analysis was to "optimize" or statistically select the "best fit" parameter values using nonlinear least-squares regression. The "best fit" parameter values are those that yield the minimum value of SS (eq. 1) and are dependent on the given set of observations.

A total of 200 potential independent parameters were defined by SDI (1997), which were many more parameters than could be estimated with the available water-level measurements. Because most data sets only support the estimation of relatively few parameters, the number of parameter values estimated generally needs to be a fraction of the number of observations used to estimate them (Hill, 1992). Therefore, the entire parameter set was divided into five individual data sets; each data set corresponds to one of the five parameters of interest. Sensitivities and correlations were then run individually for each parameter zone of the five parameters of interest. The sensitivity for each parameter-zone value was used as a measure of the "reasonableness" of estimating a parameter and as a guide for deciding which parameters should be estimated. Insensitive parameters should not be estimated because there is no basis to do so as measured by the objective function (eq. 1). Although 200 parameter zones were initially defined for the CNTB area hydrologic model, not all parameters were estimated.

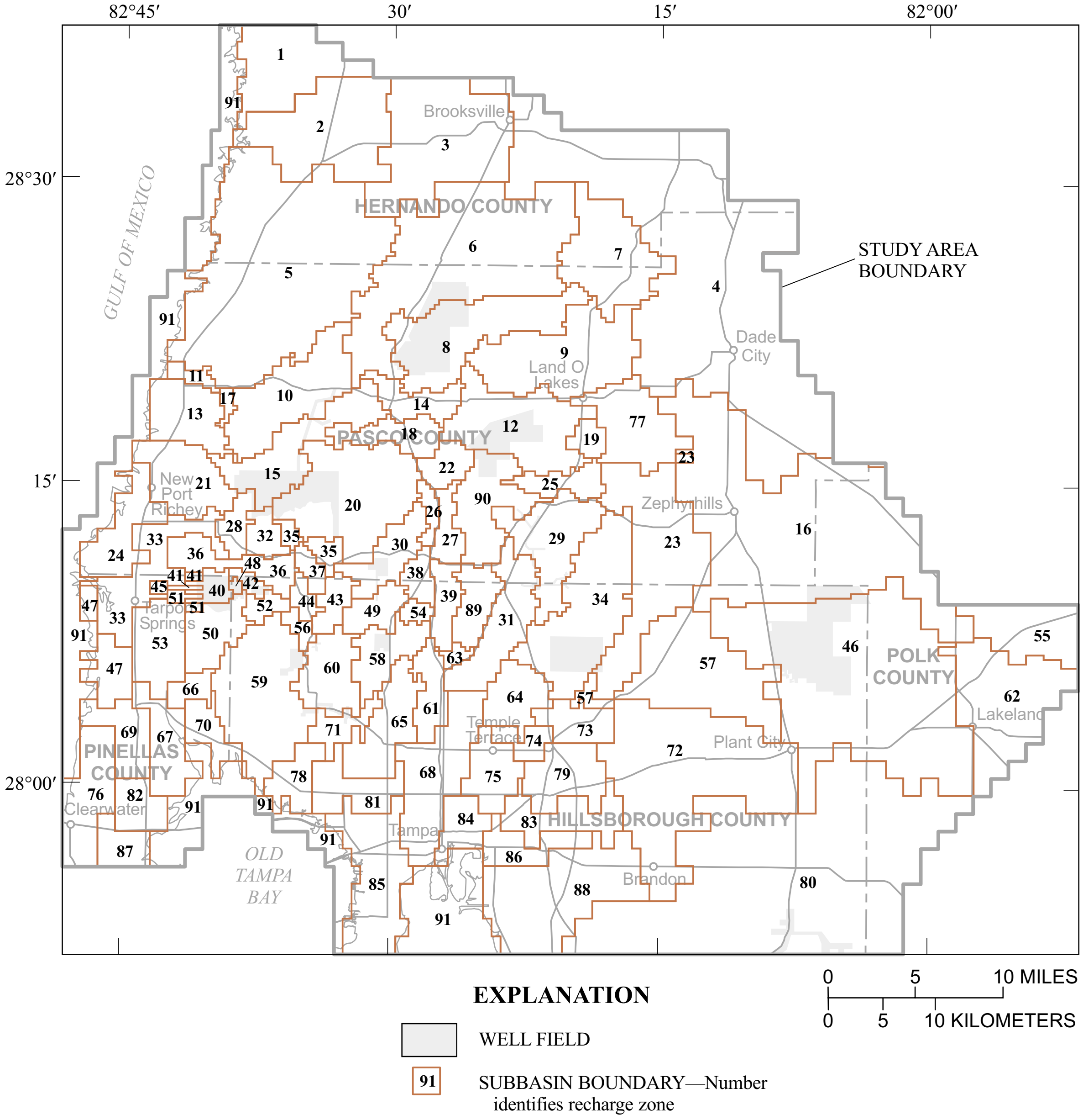


Figure 12. Watershed subbasins within the study area. (Modified from SDI Environmental Services, Inc., 1997).

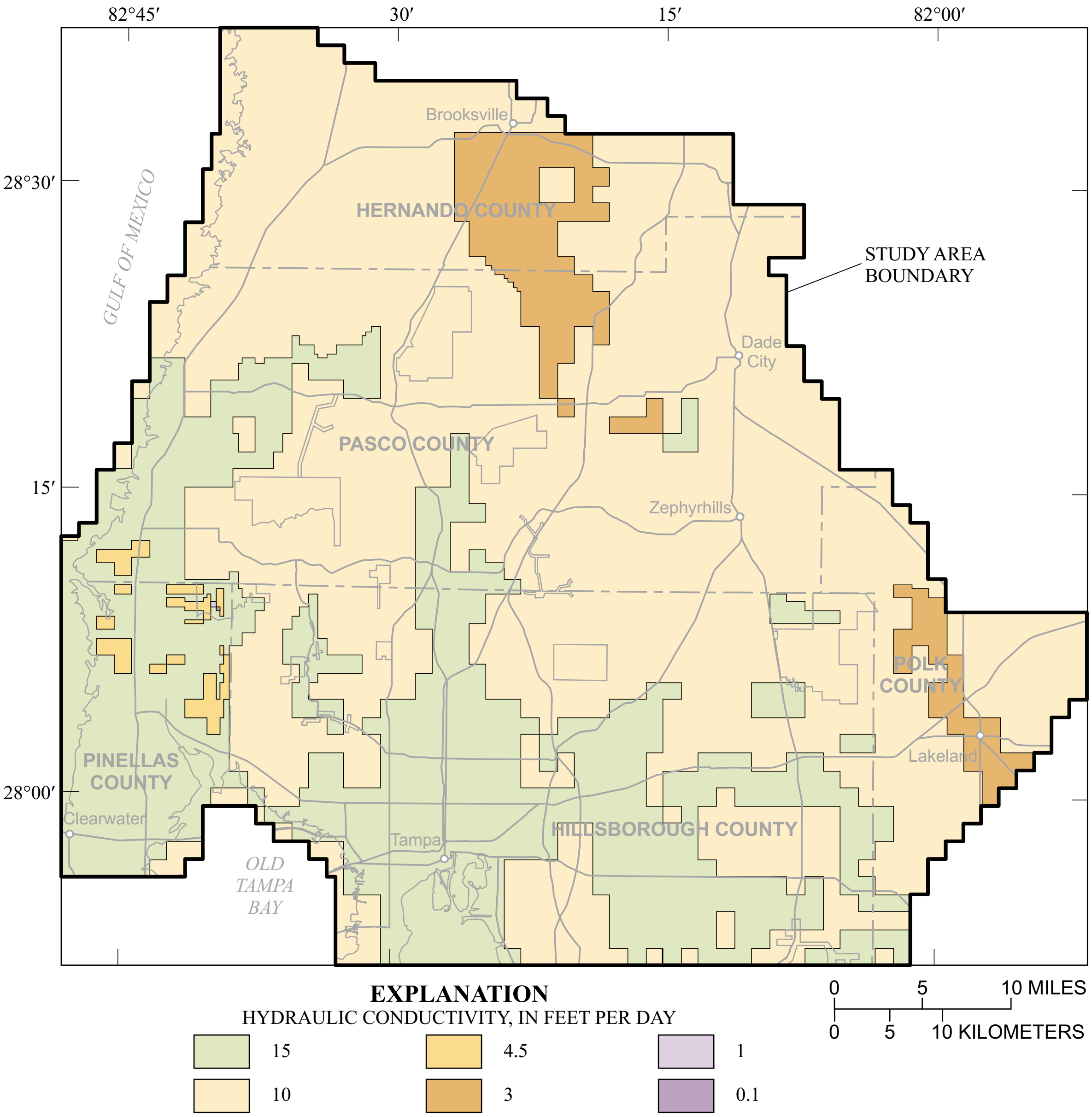


Figure 13. Calibrated hydraulic conductivity of the surficial aquifer system for the existing central northern Tampa Bay area hydrologic model. (Modified from SDI Environmental Services, Inc., 1997).

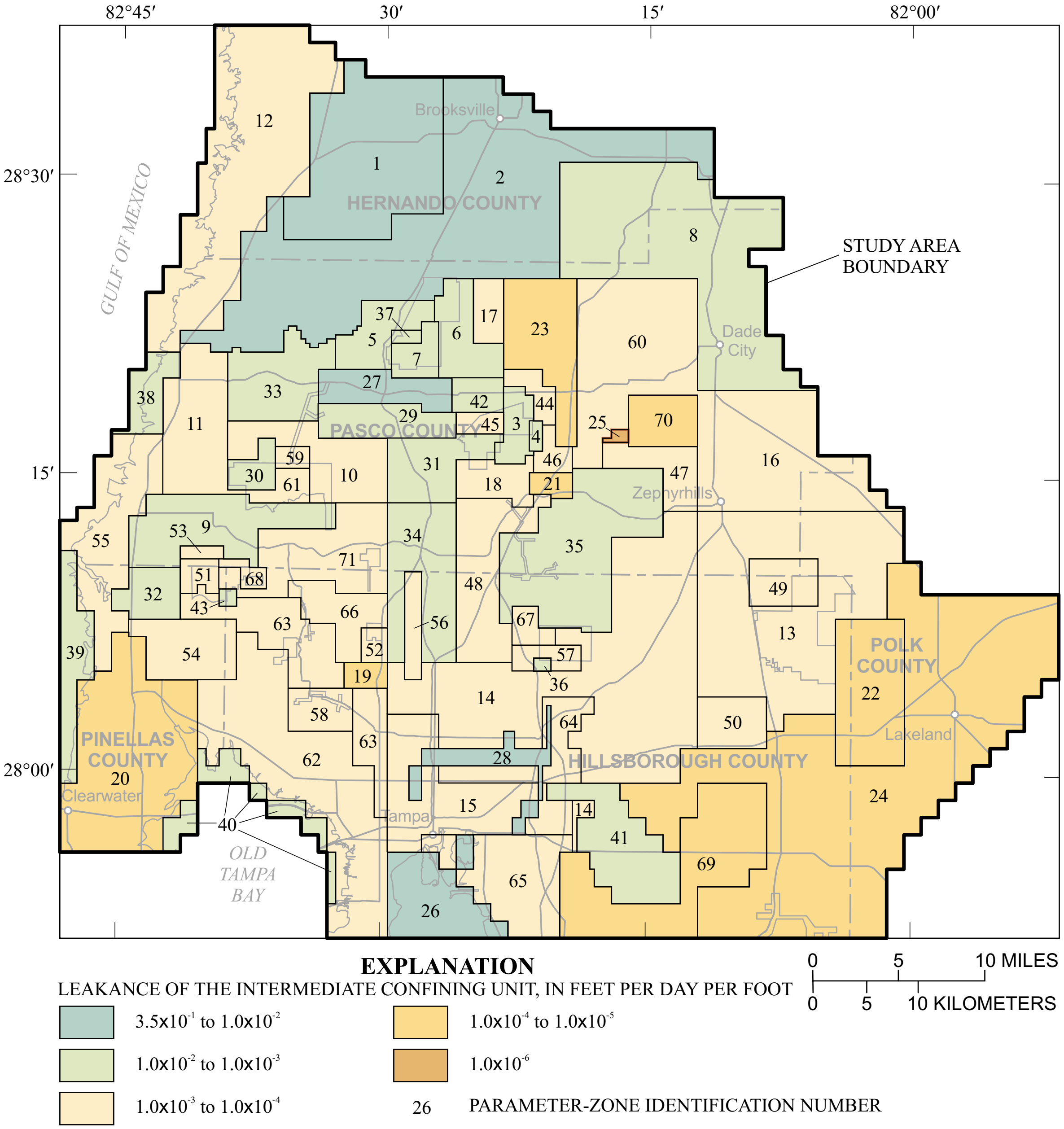


Figure 14. Calibrated leakance of the intermediate confining unit for the existing central northern Tampa Bay area hydrologic model. (Modified from SDI Environmental Services, Inc., 1997).

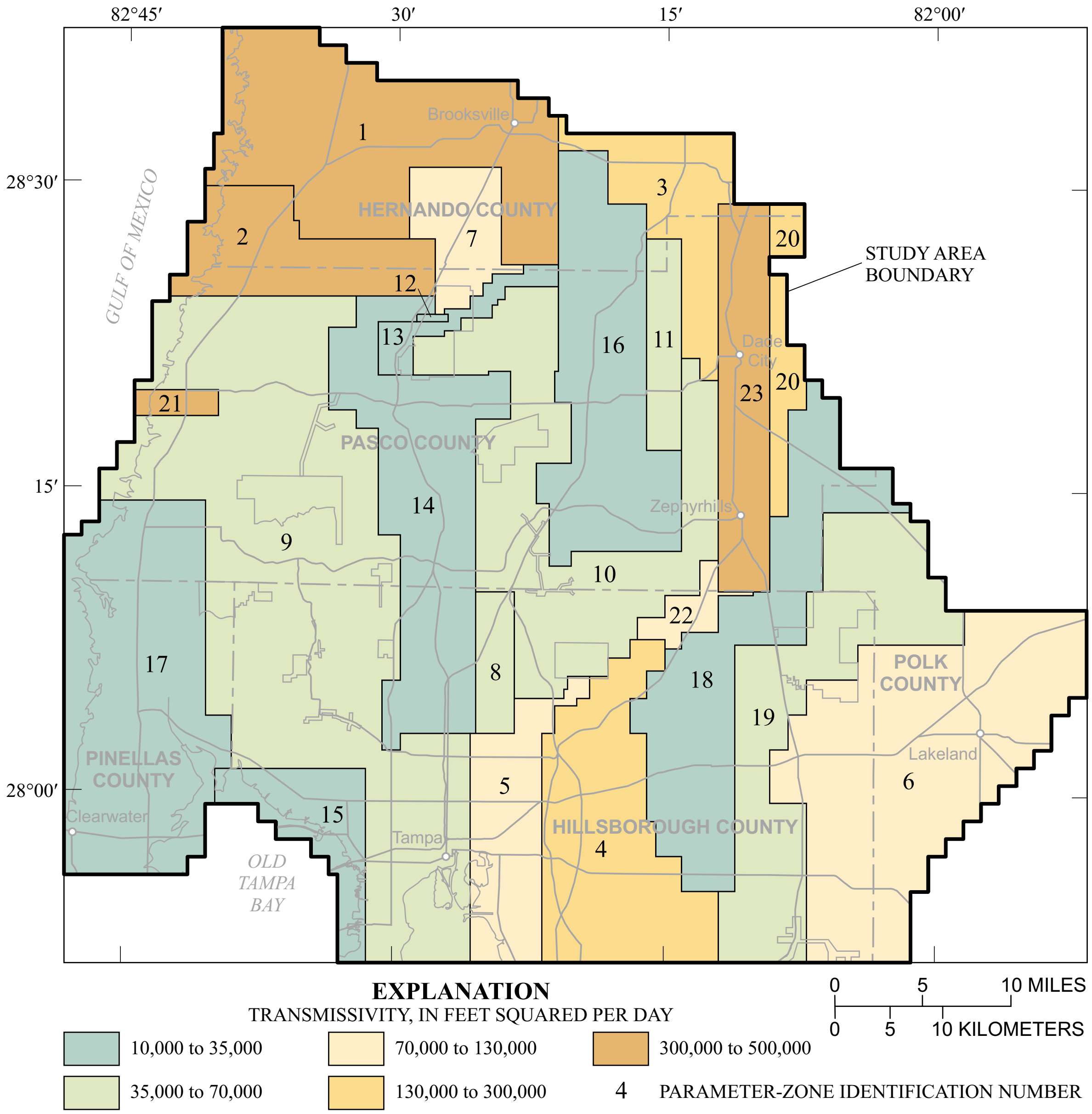


Figure 15. Calibrated transmissivity of the Upper Floridan aquifer for the existing central northern Tampa Bay area hydrologic model. (Modified from SDI Environmental Services, Inc., 1997).

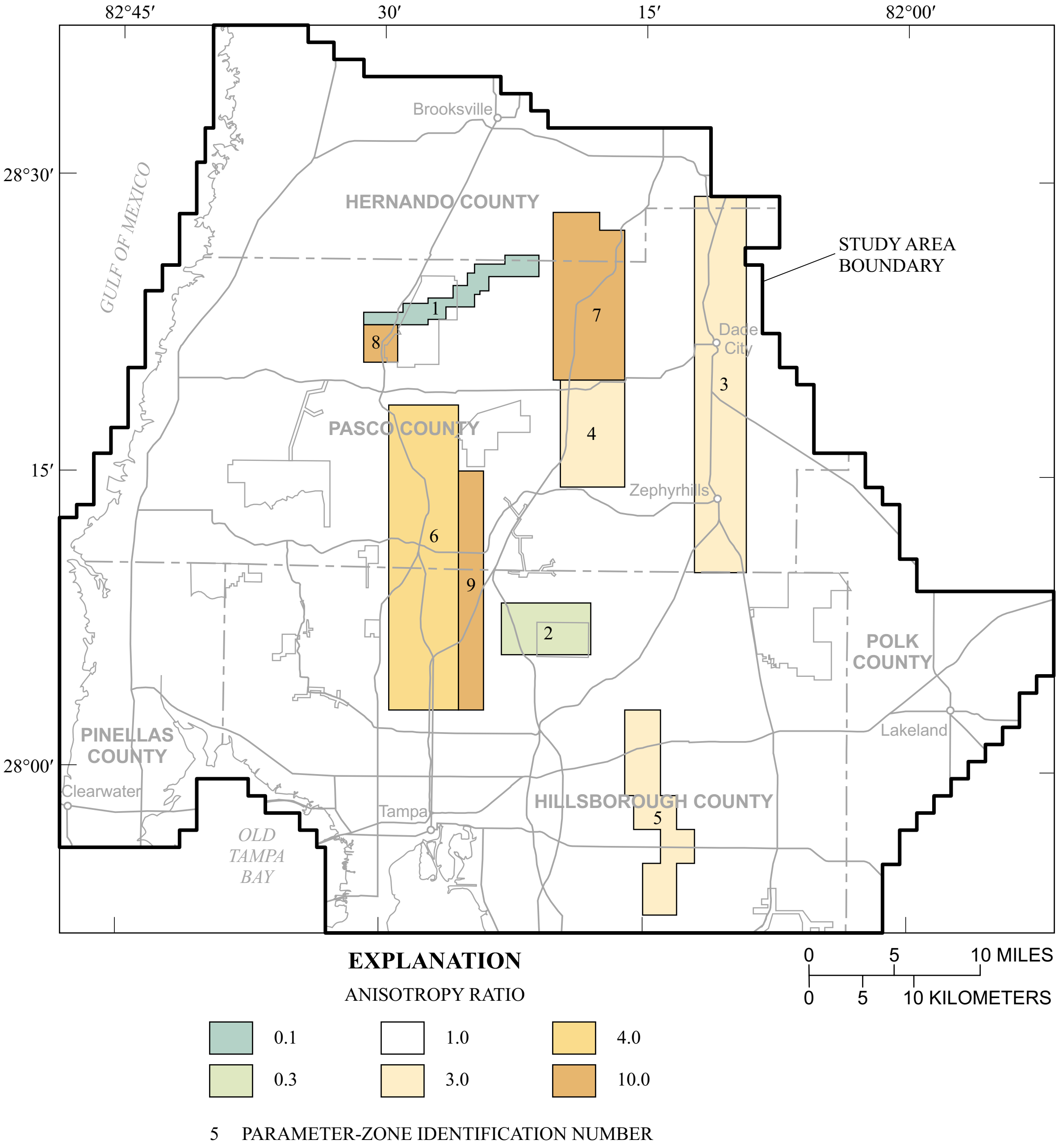


Figure 16. Calibrated anisotropy of the Upper Floridan aquifer for the existing central northern Tampa Bay area hydrologic model. (Modified from SDI Environmental Services, Inc., 1997).

Initial Parameter Sensitivities and Correlations (phase 1)

The overall sensitivity of the parameters to the observations reflect how well the parameters are defined by the observations and indicate how well the parameters will be estimated. Composite sensitivity (CS) is the statistic that is used to measure this overall sensitivity, and indicates the cumulative amount of information that the measurements contain toward the estimation of that parameter. The magnitude of the main diagonal of the covariance matrix is a rough estimate of the sensitivity of the model to a parameter. The CS of the $j^{\underline{th}}$ parameter was quantified by:

$$CS_{i,j} = \sum_{i=1}^{n} \left(\frac{\partial}{\partial x_j}(o_i) \right), \qquad (3)$$

where

$CS_{i,j}$ is the Jacobian matrix or sensitivity matrix of SS(x), and is the partial derivative of SS(x) (eq. 1) at all observations (o) with respect to parameter change (number of observations by number of parameters matrix),

n is the number of water-level comparisons, and

$\frac{\partial}{\partial x_j}(o_i)$ is the sensitivity coefficient of the i^{th} observation (o) with respect to the j^{th} parameter estimated.

For a given model and objective function, the measure calculated by eq. 3 increases as parameter sensitivity increases. Parameter sensitivity was reported in terms of the relative composite sensitivity (RCS), which is the square root of the main diagonal value divided by the maximum main diagonal for each parameter. The RCS for the j^{th} parameter was quantified by:

$$RCS_j = [(CS)_{j,j}/max(CS)_{j,j}]^{0.5} \qquad (4)$$

The most sensitive parameter has a RCS equal to 1.00 and the RCS of all other estimated parameters is less than one. The larger the value of the RCS, the more sensitive the model is to that parameter, as a whole. Parameters with larger RCS values relative to those for other parameters are likely to be easily estimated by the regression; parameters with smaller RCS values may be more difficult to estimate. Parameters with smaller RCS values also tend to have higher parameter uncertainty and broader confidence intervals. For some parameters, the available measurements may not provide enough information for estimation. If the RCS value is less than 0.02, the optimization procedure has difficulty estimating the parameter.

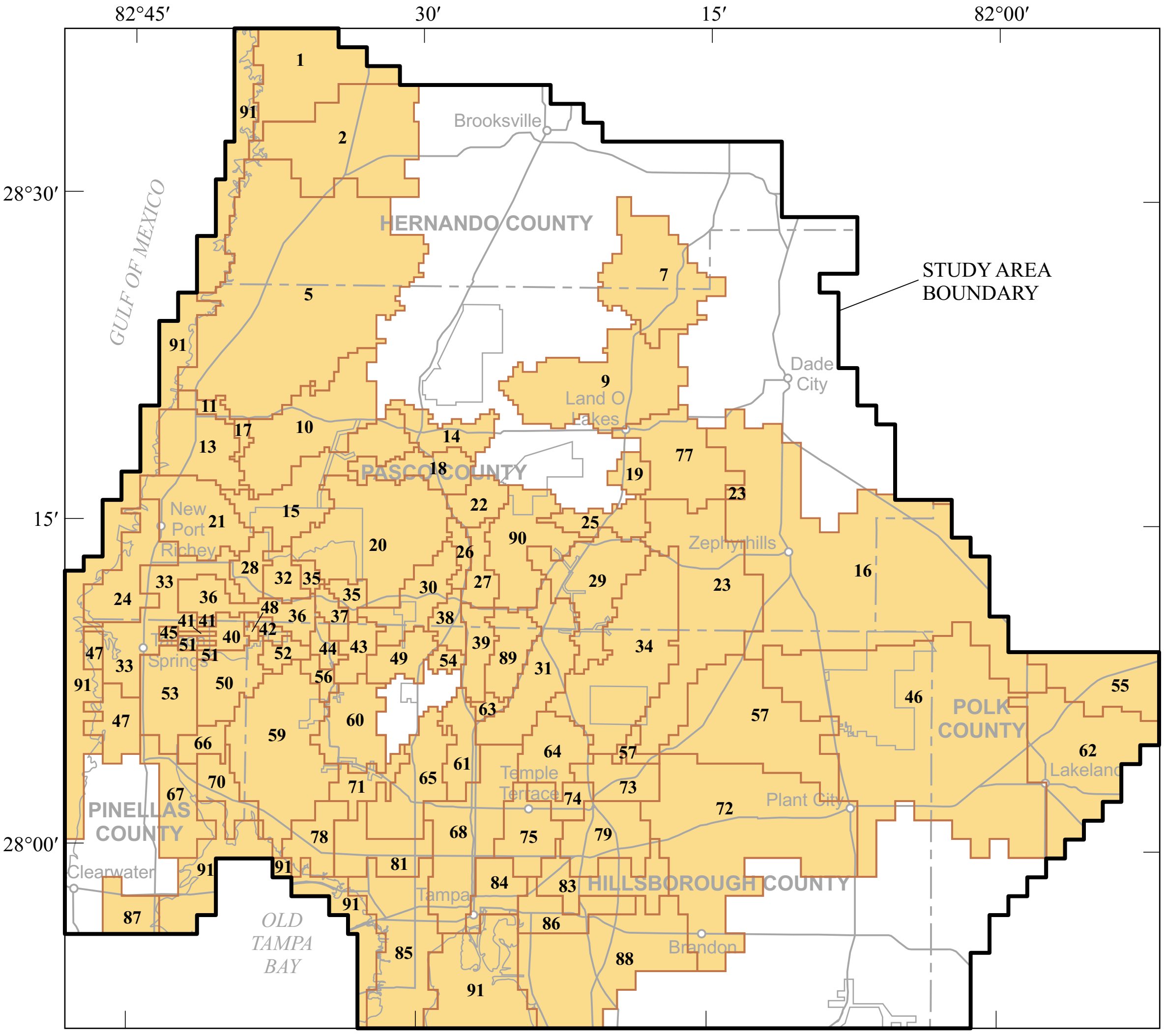
In considering model sensitivity to a particular parameter, it also is important to consider the areal size of the zone (relative to the total model area) and the number of water levels within the zone. This information along with RCS values should be considered when assessing, in a qualitative manner, the relative sensitivity of the model (either as a whole or locally) to each parameter.

Correlation between parameters indicates whether or not the parameter estimates are unique with the given model construction and observations. It is an indicator of the degree of linear dependency in the sensitivity matrix and reflects the redundancy of the problem. Correlation coefficients are calculated by inverting a matrix that is singular when correlations are -1.0 or +1.0 (Poeter and Hill, 1996). If two parameters are highly correlated, then changing the parameter values in a linearly coordinated way will result in a similar value of the objective function. Correlation coefficients greater than 0.95 usually indicate a pair of parameters are highly correlated (Hill, 1992). Parameters that are highly correlated are not desirable because they cannot be independently estimated.

The general results from the analysis described in the following sections indicate that there is insufficient observation data to independently estimate all SDI (1996) parameter values given the present zonation structure. A simpler parameter-zonation structure should be considered given the lack of information contained in the data that are available for calibration. Some possible ways of improving model calibration are to: (1) modify the defined parameter-zonation structure by omitting and/or combining parameters to be estimated; (2) carefully eliminate observation data based on evidence that the data are likely to be biased; (3) collect additional water-level data; (4) assign values to insensitive parameters, and (5) estimate the most sensitive parameters first, then using the optimized values for these parameters, estimate the entire data set (Hill, 1992, appendix B; Yager, 1993).

Recharge

Recharge to the surficial aquifer system was defined with 91 parameter zones (fig. 12); zones correspond to each of the 91 surface-water subbasins represented in the CNTB area hydrologic model. The 1987 recharge rates were derived from the surface-water model component (HSPF) and averaged 13.6 in/yr. Sensitivity values for the parameter zones, number of water-level measurements within each zone, and the areal size of each zone are shown in table 1. Results show that there are insufficient water-level data to reliably estimate the defined parameter-zone values (fig. 17 and table 1). Sensitivity is less than 0.02 for most of the parameter zones, and the small RCS values indicate that these parameters are not well defined with the available observations and given model construction. Possible solutions to improve calibration are to set parameter-zone values to specified values, estimate fewer parameters by combining zones, or collect more water-level data that will uniquely define all parameter values. Generally, the low sensitivity areas coincide with areas where the simulated water table is constrained by land surface and water levels are within 5 ft of land surface (fig. 18). Many of the parameters also are highly correlated, which limits the ability of the model to uniquely determine the parameters.



EXPLANATION

91 SUBBASIN BOUNDARY TO WHICH THE MODEL IS RELATIVELY INSENSITIVE TOWARD THE ESTIMATION OF DISCHARGE—The relative composite sensitivity is less than 0.02. Number is identifier found in table 1

Figure 17. Areas of the central northern Tampa Bay area hydrologic model that are insensitive to the estimation of recharge.

Table 1. Relative composite sensitivity, number of water-level measurements, and areal size of each recharge zone for the initial parameter values

[RCS, relative composite sensitivity; SAS, surficial aquifer system; UFA, Upper Floridan aquifer; mi^2, square miles; zone numbers are shown in figure 12]

Zone number	RCS	Number of water-level measurements			Zone area (mi^2)
		SAS	UFA	Total	
6	1.0000	7	16	23	76.62
4	0.9882	1	9	10	169.29
3	0.9882	0	2	2	46.74
82	0.0346	1	5	6	8.02
80	0.0342	7	7	14	32.85
58	0.0323	10	11	21	11.39
69	0.0255	1	4	5	11.00
76	0.0204	3	6	9	18.00
12	0.0203	13	15	28	30.06
8	0.0203	8	16	24	32.85
72	0.0199	5	10	15	70.03
46	0.0185	2	3	5	113.34
87	0.0170	3	2	5	7.01
34	0.0167	26	28	54	37.53
85	0.0158	5	10	15	27.26
5	0.0150	1	6	7	107.17
7	0.0141	0	1	1	27.22
67	0.0140	0	1	1	13.01
50	0.0131	13	12	25	11.25
57	0.0121	2	3	5	39.67
65	0.0112	2	2	4	16.93
59	0.0107	13	10	23	36.66
60	0.0106	4	4	8	14.02
54	0.0097	1	0	1	2.06
56	0.0096	2	1	3	2.44
68	0.0095	1	3	4	26.39
77	0.0091	1	1	2	19.74
16	0.0077	2	4	6	114.17
71	0.0072	1	0	1	6.25
40	0.0072	12	14	26	3.77
23	0.0060	2	2	4	44.15
88	0.0059	5	8	13	39.75
47	0.0056	1	1	2	10.51
30	0.0054	15	14	29	11.51
39	0.0052	1	0	1	6.82
61	0.0052	0	0	0	8.57
20	0.0046	8	4	12	38.08
9	0.0043	0	1	1	34.92
33	0.0042	0	1	1	20.25
28	0.0041	3	6	9	5.28
89	0.0039	2	0	2	9.19
43	0.0039	3	1	4	5.37
53	0.0039	2	2	4	14.51
38	0.0037	0	0	0	4.50
83	0.0037	1	5	6	13.88
22	0.0033	0	2	2	6.06
44	0.0032	1	2	3	2.94
15	0.0031	7	13	20	22.53
79	0.0031	3	11	14	14.63
21	0.0031	0	2	2	17.50
25	0.0030	1	2	3	7.13
90	0.0030	3	6	9	18.58
81	0.0029	1	2	3	11.98
31	0.0026	1	0	1	19.33
51	0.0026	0	0	0	1.50
10	0.0023	1	1	2	27.16
14	0.0023	2	3	5	8.75
29	0.0023	1	1	2	21.55
2	0.0022	0	3	3	37.71
64	0.0022	2	0	2	11.47
49	0.0020	0	1	1	7.13
42	0.0020	2	5	7	2.00
27	0.0019	0	1	1	5.75
36	0.0017	0	0	0	11.20
84	0.0011	0	0	0	7.99
66	0.0011	3	2	5	4.06
26	0.0011	0	0	0	2.94
73	0.0010	0	4	4	8.74
48	0.0010	2	2	4	0.57
18	0.0008	0	0	0	9.56
52	0.0006	1	0	1	3.25
13	0.0006	0	4	4	15.02
35	0.0004	0	0	0	4.63
75	0.0004	0	0	0	11.13
78	0.0004	1	0	1	8.52
86	0.0003	0	2	2	9.62
74	0.0003	0	1	1	4.87
19	0.0003	0	0	0	3.72
32	0.0003	0	0	0	5.00
63	0.0003	0	0	0	1.69
45	0.0002	0	0	0	0.76
1	0.0002	0	0	0	25.03
70	0.0002	0	0	0	7.50
37	0.0002	0	1	1	3.26
24	0.0002	0	1	1	15.27
55	0.0002	0	0	0	18.26
41	0.0002	0	0	0	0.91
17	0.0002	0	0	0	1.36
62	0.0001	0	1	1	35.86
11	0.0001	0	0	0	2.56
91	0.0001	1	2	3	109.62

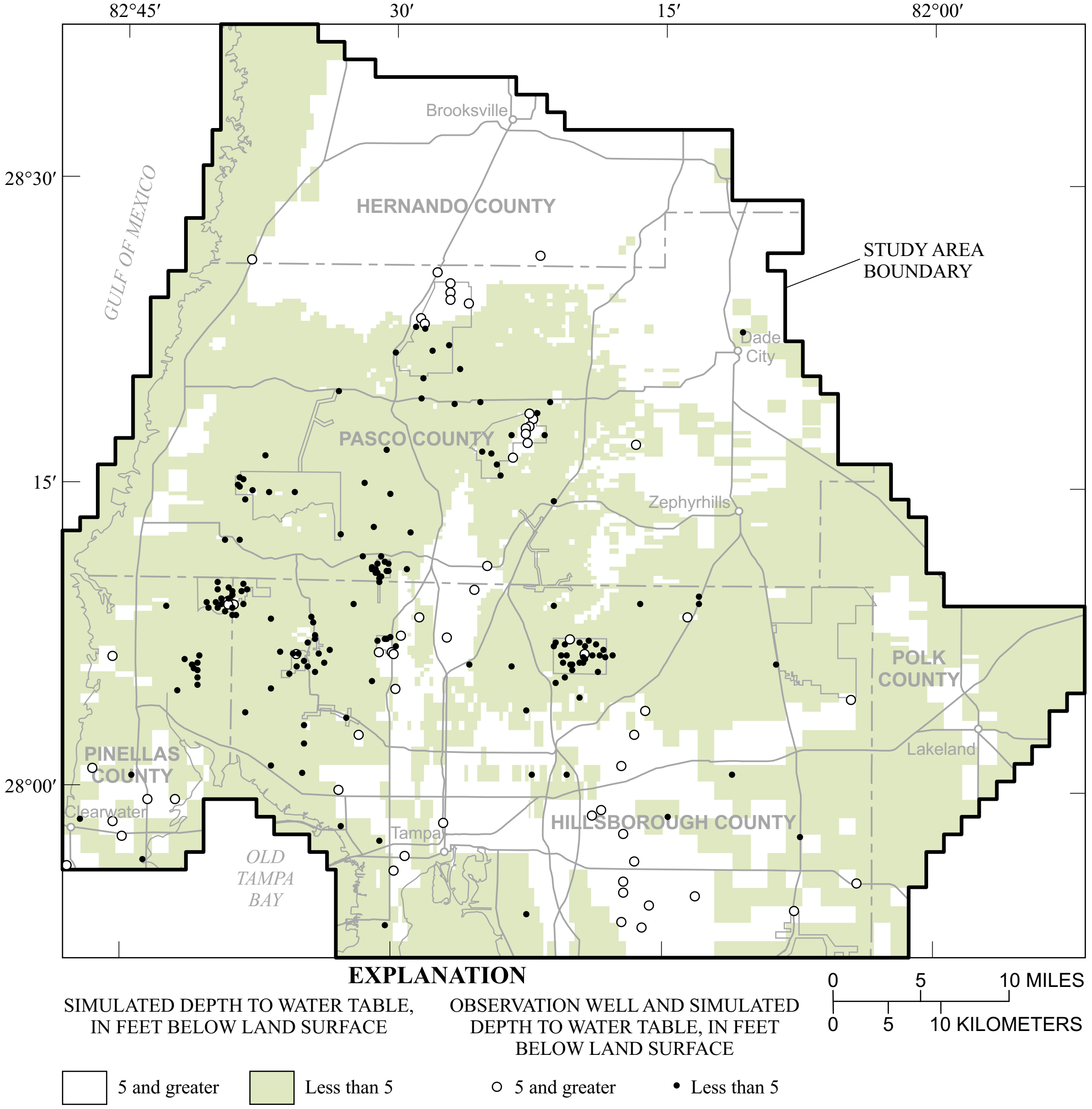


Figure 18. Simulated depth to water table using the initial central northern Tampa Bay area hydrologic model parameter values, calendar year 1987.

Hydraulic Conductivity of the Surficial Aquifer System

Hydraulic conductivity (K) of the surficial aquifer system was defined with six parameter zones (fig. 13). Sensitivity values for the parameter zones, zone areas, and number of water-level measurements within each zone are shown in table 2. Regression results indicate that the available water-level data provide sufficient information to reliably estimate hydraulic conductivity of the surficial aquifer system in three of the five parameter zones (RCS > 0.02). Sensitivity is highest for the high K parameters (15.0, 10.0, and 4.5 ft/day) and is lowest for the low K parameters (0.1, 1.0, and 3.0 ft/d).

For improved calibration, the parameter value for the low sensitivity zones should be set to the specified value, combined with adjacent zones, or more water-level measurements will need to be added to the regression. The low sensitivity for the 1.0, 0.1, and 3.0 ft/d parameter zones is primarily due to a lack of water-level measurements within these zones and the small parameter-zone area relative to total model area. The area of the zones is less than 5 percent of the total model area and only six water-level measurements are within the zones. The K-parameter zones also are not highly correlated to one another. The highest degree of correlation is between the 1.0 and 0.1 ft/d hydraulic conductivity zones (r = 0.91).

Table 2. Relative composite sensitivity, number of water-level measurements, and areal size of each hydraulic conductivity zone of the surficial aquifer system for the initial parameter values

[K, hydraulic conductivity; RCS, relative composite sensitivity; SAS, surficial aquifer system; UFA, Upper Floridan aquifer; mi^2, square miles; ft/d, foot per day; zones are shown in figure 13]

K-Parameter Zone	RCS	Number of water-level measurements		Zone area (mi^2)
		SAS	UFA	
15.0 ft/d	1.000	77	119	610.71
10.0 ft/d	0.700	138	200	1,360.06
4.5 ft/d	0.044	7	6	17.32
3.0 ft/d	0.017	1	4	105.83
1.0 ft/d	0.008	0	0	0.06
0.1 ft/d	0.003	0	1	0.06

Leakance of the Intermediate Confining Unit

Leakance of the intermediate confining unit was defined by 71 parameter zones (fig. 14). Sensitivity values for the parameter zones, number of water-level measurements within each zone, and the areal size of each zone are shown in table 3. Regression results indicate that the available water-level data provide sufficient information to reliably estimate leakance of the intermediate confining unit for most parameter zones; however, estimating all leakance-zone values simultaneously may be impossible due to parameter insensitivity (fig. 19 and table 3). It also may not be reasonable to estimate leakance for several parameter zones given the lack of sensitivity of the parameter-zone values.

Table 3. Relative composite sensitivity, number of water-level measurements, and areal size of each leakance zone of the intermediate confining unit for the initial parameter values

[RCS, relative composite sensitivity; SAS, surficial aquifer system; UFA, Upper Floridan aquifer; mi^2, square miles; zone numbers are shown in figure 14]

Zone number	RCS	Number of water-level measurements			Zone area (mi^2)
		SAS	UFA	Total	
20	1.0000	9	18	27	74.78
71	0.4400	26	27	53	32.60
63	0.4300	18	13	31	35.71
52	0.3600	4	4	8	3.01
24	0.3400	5	7	12	213.3
69	0.3200	2	4	6	50.73
14	0.2600	20	24	44	136.63
15	0.2300	2	6	8	40.21
62	0.2300	10	12	22	79.06
43	0.2200	7	6	13	1.01
66	0.2100	6	8	14	14.63
58	0.1800	4	1	5	9.38
51	0.1700	5	1	10	4.24
34	0.1500	4	4	8	31.78
56	0.1400	1	1	2	6.26
55	0.1300	1	4	5	38.65
9	0.1100	3	3	6	33.29
19	0.1100	2	0	2	3.74
39	0.1100	0	1	1	17.51
40	0.1100	0	1	1	15.95
57	0.1100	7	6	13	5.24
13	0.0950	2	4	6	101.86
65	0.0930	1	3	4	31.79
5	0.0910	5	8	13	14.19
41	0.0890	8	13	21	29.46
23	0.0860	0	4	4	28.74
45	0.0780	1	3	4	3.43
54	0.0770	9	8	17	19.42
67	0.0730	4	5	9	4.39
35	0.0700	5	7	12	58.21
68	0.0680	0	3	3	2.75
60	0.0670	0	3	3	57.27
6	0.0610	2	4	6	15.15
8	0.0610	1	6	7	106.24
16	0.0610	0	2	2	59.94
3	0.0540	8	7	15	7.55
30	0.0540	8	15	23	6.07
7	0.0490	3	6	9	6.76
10	0.0430	3	2	5	25.34
32	0.0430	1	1	2	10.26
48	0.0430	4	0	4	29.97
4	0.0410	1	0	1	1.31
42	0.0370	1	1	2	6.00
31	0.0340	3	8	11	18.64
44	0.0320	1	1	2	5.18
64	0.0320	1	5	6	10.13
70	0.0290	0	0	0	11.98
2	0.0280	6	16	22	162.92
12	0.0250	0	4	4	98.88
61	0.0210	1	1	2	5.45
18	0.0200	1	4	5	10.14
27	0.0200	3	3	6	14.63
11	0.0190	0	5	5	30.31
36	0.0180	1	1	2	0.75
53	0.0180	0	0	0	1.89
46	0.0160	0	0	0	4.19
49	0.0150	0	2	2	10.98
17	0.0140	0	0	0	6.58
50	0.0110	0	0	0	12.01
28	0.0100	1	9	10	12.46
37	0.0100	0	0	0	1.33
21	0.0095	1	1	2	3.44
33	0.0094	0	1	1	24.59
47	0.0082	0	0	0	12.26
29	0.0071	0	0	0	14.96
59	0.0068	0	0	0	2.51
26	0.0062	0	1	1	26.98
22	0.0060	0	0	0	34.02
1	0.0059	0	3	3	71.78
25	0.0056	1	1	2	0.88
38	0.0024	0	0	0	10.17

Generally, sensitivity is highest for parameter zones that have an abundance of observation data within the zones. Leakance zones also are not strongly correlated to one another. The strongest correlation is between zones 60 and 70 (r = 0.87). The second highest correlation is between zones 1 and 25 (r = 0.86).

Transmissivity of the Upper Floridan Aquifer

Transmissivity of the Upper Floridan aquifer was defined by 23 parameter zones (fig. 15). Sensitivity values for the parameter zones, number of water-level measurements within each zone, and the areal size of each zone are shown in table 4. Regression results indicate that the available water-level data provide sufficient information to reliably estimate transmissivity of the Upper Floridan aquifer in all but two isolated zones (20 and 21) (fig. 20), given the lack of sensitivity. Zone 21 includes specified head boundary cells while zone 20 includes river boundary cells (figs. 7 and 8). Sensitivity is low because these boundary conditions prevent the simulated water level from changing substantially for different parameter values. The low sensitivity also is due to limited water-level measurements within each of the zones. Transmissivity zones also are not strongly correlated. The strongest correlation is between zones 23 and 20 (r = 0.90). The second highest correlation is between zones 2 and 13 (0.87).

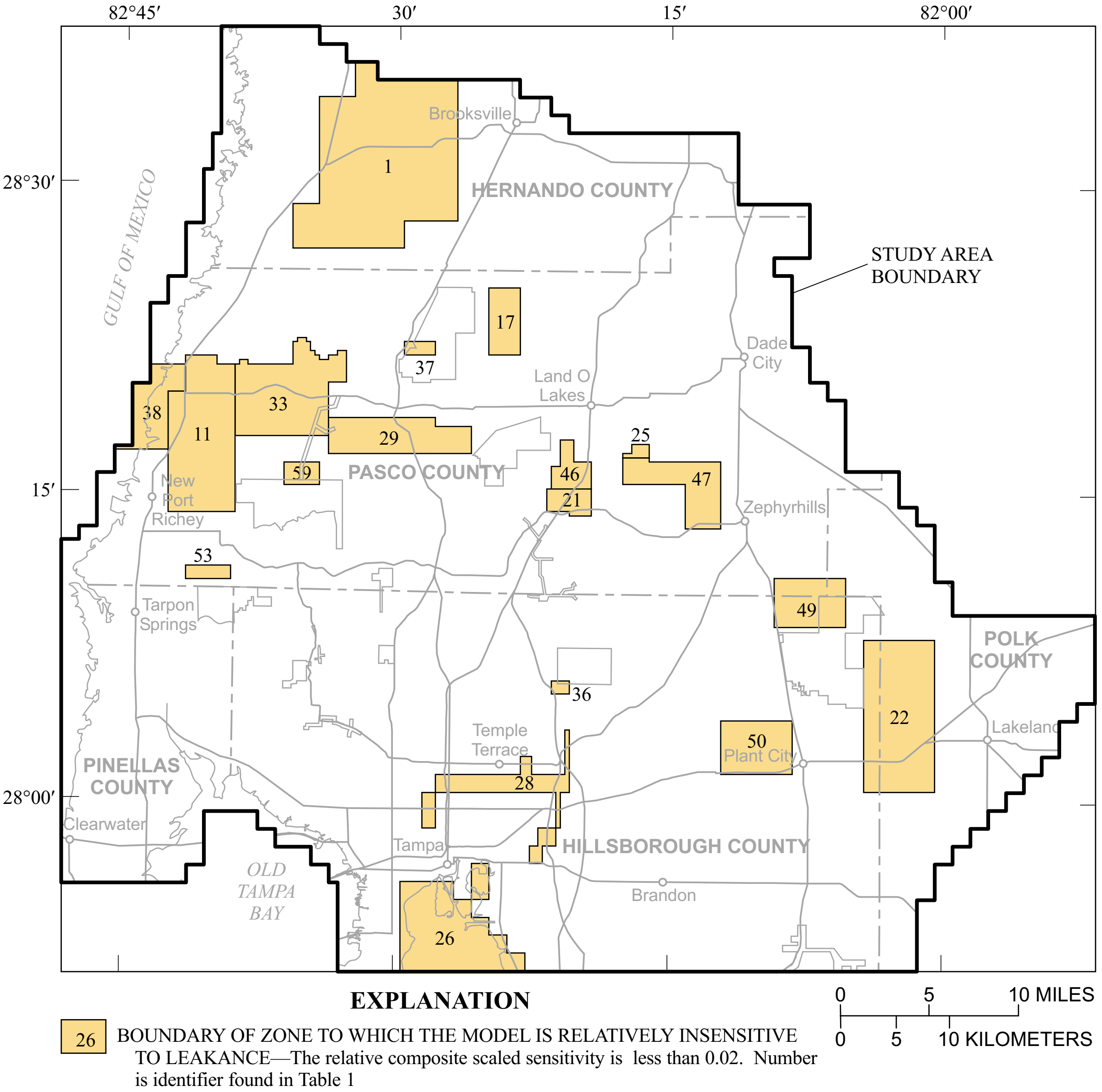
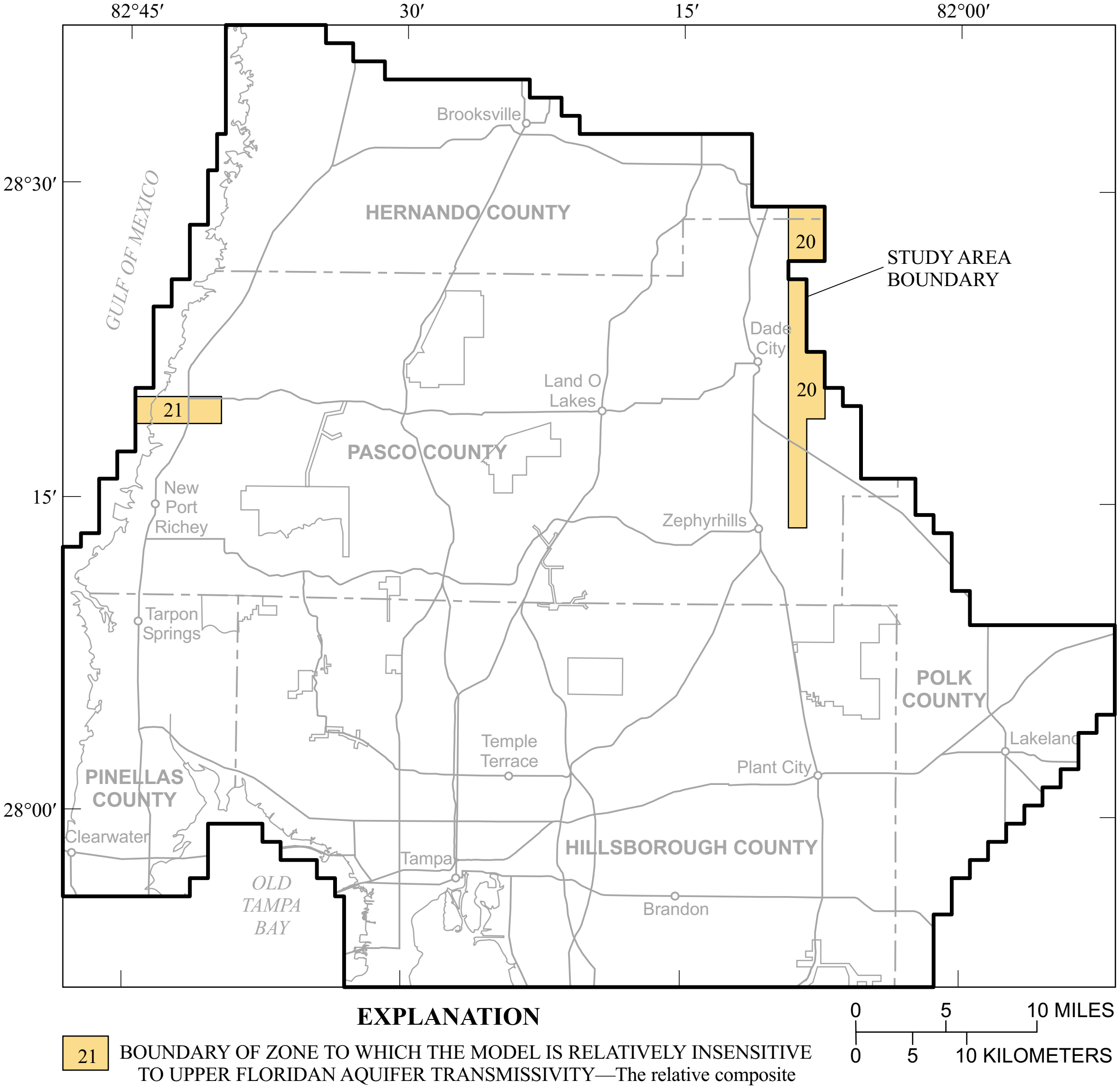


Figure 19. Areas of the central northern Tampa Bay area hydrologic model that are insensitive to the estimation of leakance.

Table 4. Relative composite sensitivity, number of water-level measurements, and areal size of each transmissivity zone of the Upper Floridan aquifer for the initial parameter values

[RCS, relative composite sensitivity; SAS, surficial aquifer system; UFA, Upper Floridan aquifer; mi^2, square miles; zone numbers are shown in figure 15]

Zone number	RCS	Number of water-level measurements			Zone area (mi^2)
		SAS	UFA	Total	
1	1.000	1	5	6	162.02
9	0.571	92	109	201	365.50
2	0.473	1	3	4	62.90
10	0.470	47	50	97	156.92
18	0.290	3	8	11	121.91
17	0.268	20	29	49	171.26
16	0.226	2	8	10	121.51
14	0.216	14	21	35	127.59
6	0.214	2	3	5	206.97
4	0.202	15	31	46	115.97
7	0.200	5	16	21	34.46
13	0.188	4	4	8	15.07
19	0.176	3	6	9	127.10
23	0.143	1	6	7	65.92
3	0.091	0	2	2	54.35
8	0.088	1	0	1	18.01
5	0.078	4	11	15	58.81
11	0.078	0	2	2	24.01
22	0.047	3	2	5	11.36
15	0.045	4	3	7	40.50
12	0.044	1	3	4	0.88
21	0.019	0	4	4	7.12
20	0.012	0	0	0	23.24
19	0.176	3	6	9	127.10



EXPLANATION

21	BOUNDARY OF ZONE TO WHICH THE MODEL IS RELATIVELY INSENSITIVE TO UPPER FLORIDAN AQUIFER TRANSMISSIVITY—The relative composite scaled sensitivity is less than 0.02. Number is identifier found in Table 1

Figure 20. Areas of the central northern Tampa Bay area hydrologic model that are insensitive to the estimation of transmissivity of the Upper Floridan aquifer.

Anisotropy of the Upper Floridan Aquifer

Anisotropy of the Upper Floridan aquifer was defined by nine parameters zones (fig. 16). Sensitivity values for the parameter zones, number of water-level measurements within each zone, and the areal size of each zone are shown in table 5. Regression results indicate that available water-level data provide sufficient information to reliably estimate anisotropy of the Upper Floridan aquifer for most parameter-zone values. Generally, sensitivity is highest for parameter zones that have an abundance of observation measurements within the zones. Parameters also are not highly correlated to one another ($r \leq 0.25$). In another simulation, the degree to which anisotropy and transmissivity zones of the Upper Floridan aquifer are correlated was tested. Regression results indicate a strong negative correlation (-0.98) between anisotropy of the Upper Floridan aquifer in zones 3 and 9 and transmissivity of the Upper Floridan aquifer in zones 8 and 23, respectively. The high correlation associated with these zones preclude independent estimation of them. The third highest correlation is between anisotropy zone 8 and transmissivity zone 13 (-0.84).

Table 5. Relative composite sensitivity, number of water-level measurements, and areal size of each Upper Floridan aquifer anisotropy zone for the initial parameter values

[Kx/Ky, horizontal anisotropy ratio; RCS, relative composite sensitivity; SAS, surficial aquifer system; UFA, Upper Floridan aquifer; mi^2, square miles; zone numbers are shown in figure 16]

Kx/Ky Parameter zone	Kx/Ky	RCS	Number of water-level measurements		Zone area (mi^2)
			SAS	UFA	
3	3.0	1.000	1	6	39.96
2	0.3	0.821	24	25	15.77
9	10.0	0.801	2	0	21.02
6	4.0	0.759	5	10	71.06
1	0.1	0.710	4	7	11.46
5	3.0	0.573	2	3	25.00
7	4.0	0.361	0	1	71.06
4	3.0	0.161	1	1	23.45
8	10.0	0.071	1	0	4.49

Hydraulic–Head Sensitivity

A second sensitivity analysis was performed in addition to computing the relative composite sensitivities. The model response investigated in the sensitivity analysis was hydraulic head. The parameters selected for testing were recharge, hydraulic conductivity of the surficial aquifer system, leakance of the intermediate confining unit, transmissivity of the Upper Floridan aquifer, and anisotropy of the Upper Floridan aquifer. Hydraulic-head sensitivities are a measure of the change in simulated water levels due to changes in parameter values. Results from this analysis can suggest which model inputs are likely to have improved parameter estimates, and can be used to identify areas where additional data are most likely to effect simulated water levels. If the analysis shows that the model is not sensitive to changes in certain parameters, efforts to improve parameter estimates in the modeled area would not improve the simulation capability of the model. Conversely, if the sensitivity analysis shows that the model is sensitive to changes in a particular parameter, additional data collection and analysis to better define or verify the parameter values in the model area could result in improved simulation capability. Collection of water-level data in areas of high sensitivity would be more valuable than obtaining water-level data in areas of low sensitivity.

Model sensitivity was described in terms of the amount that water levels would change with a 2-percent increase in the parameter value (figs. 21-25). Water-level change was calculated for the entire model and for each layer so that the relative sensitivities of the units could be compared.

The spatial patterns of the 2-percent sensitivities of simulated water levels in layers 1 and 2 to recharge are similar to each other (fig. 21) and are positive (water-level increase). The increase in recharge results in a corresponding increase in water levels due to increased flux through the flow system. To transmit this increased flux through the ground-water system, the hydraulic gradient steepens, which requires higher water levels. In the area southeast of Brooksville (fig. 21), water levels in layer 1 show little or no change. This is an area of the model where the surficial aquifer system is thin and discontinuous and only isolated, perched water-table conditions exist. Consequently, the Upper Floridan aquifer is unconfined, and recharge is applied to layer 2 and not to layer 1. Simulated water levels generally are sensitive to changes in recharge. The absolute mean water-level change was 0.26 ft for the surficial aquifer system and 0.18 ft for the Upper Floridan aquifer.

The spatial patterns of the 2-percent sensitivities of simulated water levels in layers 1 and 2 to hydraulic conductivity of the surficial aquifer system are different from each other and are mostly negative (water-level decrease) (fig 22). The negative values indicate that in response to an increase in hydraulic conductivity, water levels would decline, resulting in a flattening of the lateral hydraulic gradient through layer 1. Water levels in layer 2 decrease in response to a decrease in flux due to lower surficial aquifer system water levels. Simulated water levels are generally insensitive to changes in hydraulic conductivity of the surficial aquifer system. The absolute mean water-level change was 0.01 ft for the surficial aquifer system and 0.003 ft for the Upper Floridan aquifer.

The 2-percent sensitivities of simulated water levels in layers 1 and 2 to leakance of the intermediate confining unit show different patterns, and are mostly negative (water-level decrease) for layer 1 and positive (water-level increase) for layer 2 (fig. 23). These spatial patterns result because if leakance is increased, more of the specified recharge will flow through the intermediate confining unit, thus lowering water levels in layer 1 and raising water levels in layer 2. Simulated leakage rate through the intermediate confining unit provides a better indication of the quantity and spatial distribution of the flux between the surficial aquifer system and the Upper Floridan aquifer. Figure 26 illustrates that the majority of the study area is dominated by diffuse downward leakage to the Upper Floridan aquifer. Hence, an overall increase in leakance of the intermediate confining unit or transmissivity of the Upper Floridan aquifer will result in an overall decline in water levels. The negative water levels in layer 1 are larger than the positive water levels in layer 2, which is a reflection of permeability contrasts between the layers. Simulated water levels are generally sensitive to changes in leakance of the intermediate confining unit. The absolute mean water-level change was 0.04 ft for the surficial aquifer system and 0.04 ft for the Upper Floridan aquifer.

The spatial patterns of the 2-percent sensitivities of simulated water levels in layers 1 and 2 to transmissivity of the Upper Floridan aquifer are similar to each other and are mostly negative (water-level decrease) (fig. 24). Because recharge to the surficial aquifer system does not change when transmissivity of the Upper Floridan aquifer changes, the hydraulic gradient should decrease proportionately for the same amount of water to be conveyed laterally through the Upper Floridan aquifer. The water-level change in layer 1 is similar to the water-level change in layer 2 because the vertical leakance between layers 1 and 2 is relatively large. In addition, the spatial pattern of water-level change for transmissivity is similar to that for recharge (compare figs. 21 and 25) because the ground-water system is dominated by leakage to the Upper Floridan aquifer in the study area. Simulated water levels are generally sensitive to changes in transmissivity of the Upper Floridan aquifer. The absolute mean water-level change was 0.08 ft for the surficial aquifer system and 0.14 ft for the Upper Floridan aquifer.

The spatial patterns of the 2-percent sensitivities of simulated water levels in layers 1 and 2 to anisotropy of the Upper Floridan aquifer are similar to each other and mostly negative (water-level decline) (fig. 25). Because flux in the system does not change substantially with a change in anisotropy of the Upper Floridan aquifer, the change in anisotropy causes the lateral hydraulic gradient to change proportionately for the same amount of water transmitted laterally. Water-level changes are greatest in model cells where anisotropy is not equal to one (compare figs. 16 and 26). Overall, simulated water levels are insensitive to changes in this parameter. The absolute mean water-level change was 0.01 ft for the surficial aquifer system and 0.02 ft for the Upper Floridan aquifer.

In summary, the simulated water levels are most sensitive to changes in recharge and transmissivity of the Upper Floridan aquifer. In third place of importance is leakance of the intermediate confining unit. The least important factors are hydraulic conductivity of the surficial aquifer system and anisotropy of the Upper Floridan aquifer.

Optimal Estimates of Parameter Values (phase 2)

A total of 96 parameter zones were selected for parameter estimation by nonlinear least-squares regression. Based on the RCS and correlation values and the consideration of water-level data availability, this set of parameters includes most of the important system characteristics. Sensitivities and correlation values, however, may be different for different parameter structures. Multipliers were used to modify the initial value of hydraulic conductivity of the surficial aquifer system, leakance of the intermediate confining unit, transmissivity of the Upper Floridan aquifer, or anisotropy of the Upper Floridan aquifer by a fixed amount in the zone assigned to each parameter. Initial values for all parameters were set equal to their calibrated values in the existing CNTB area hydrologic model (SDI, 1997).

Recharge was assumed to be known and was specified as simulated by SDI (1997). Recharge was

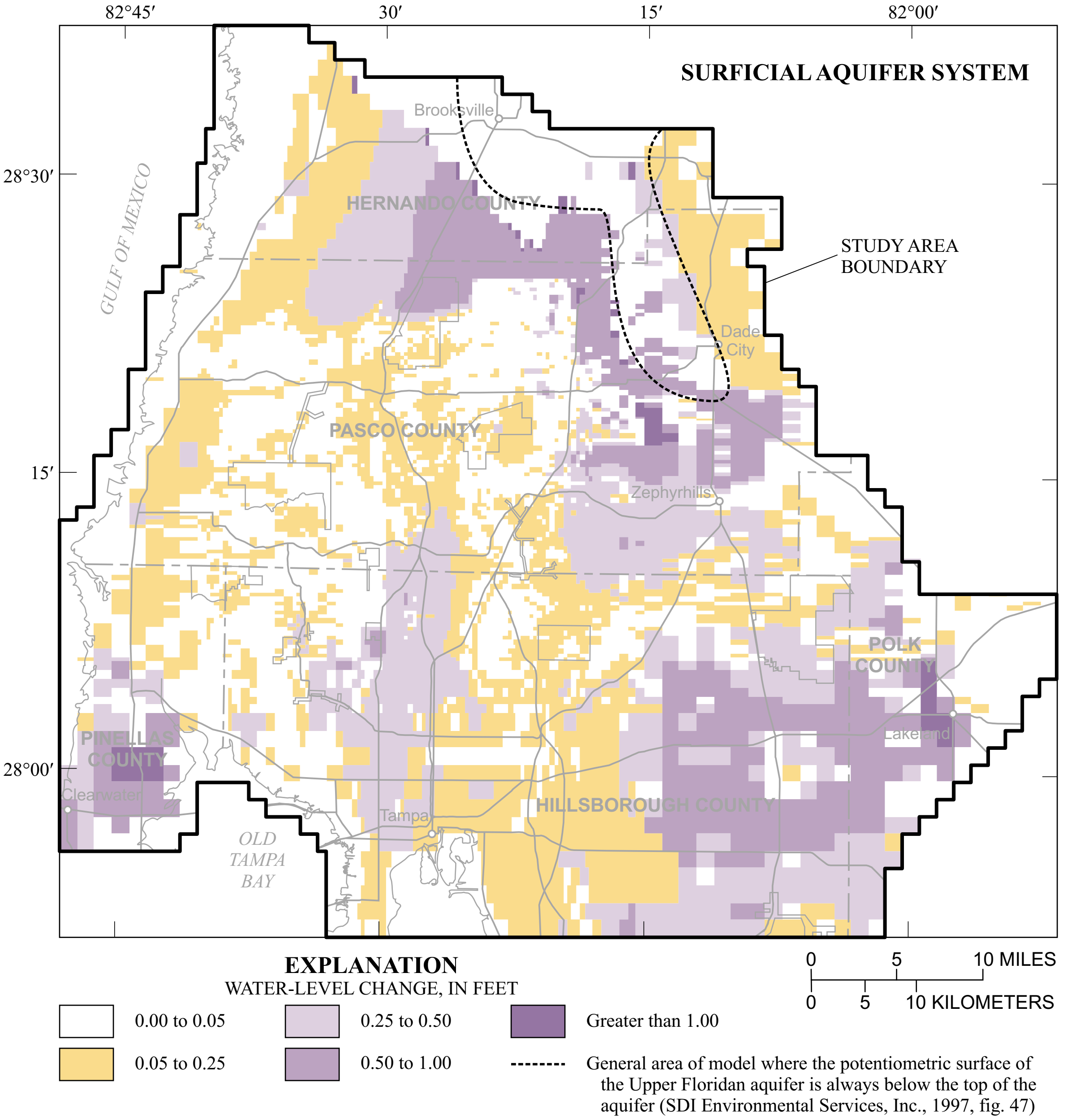


Figure 21A. Sensitivity of simulated water levels to a 2-percent increase in the initial value of recharge.

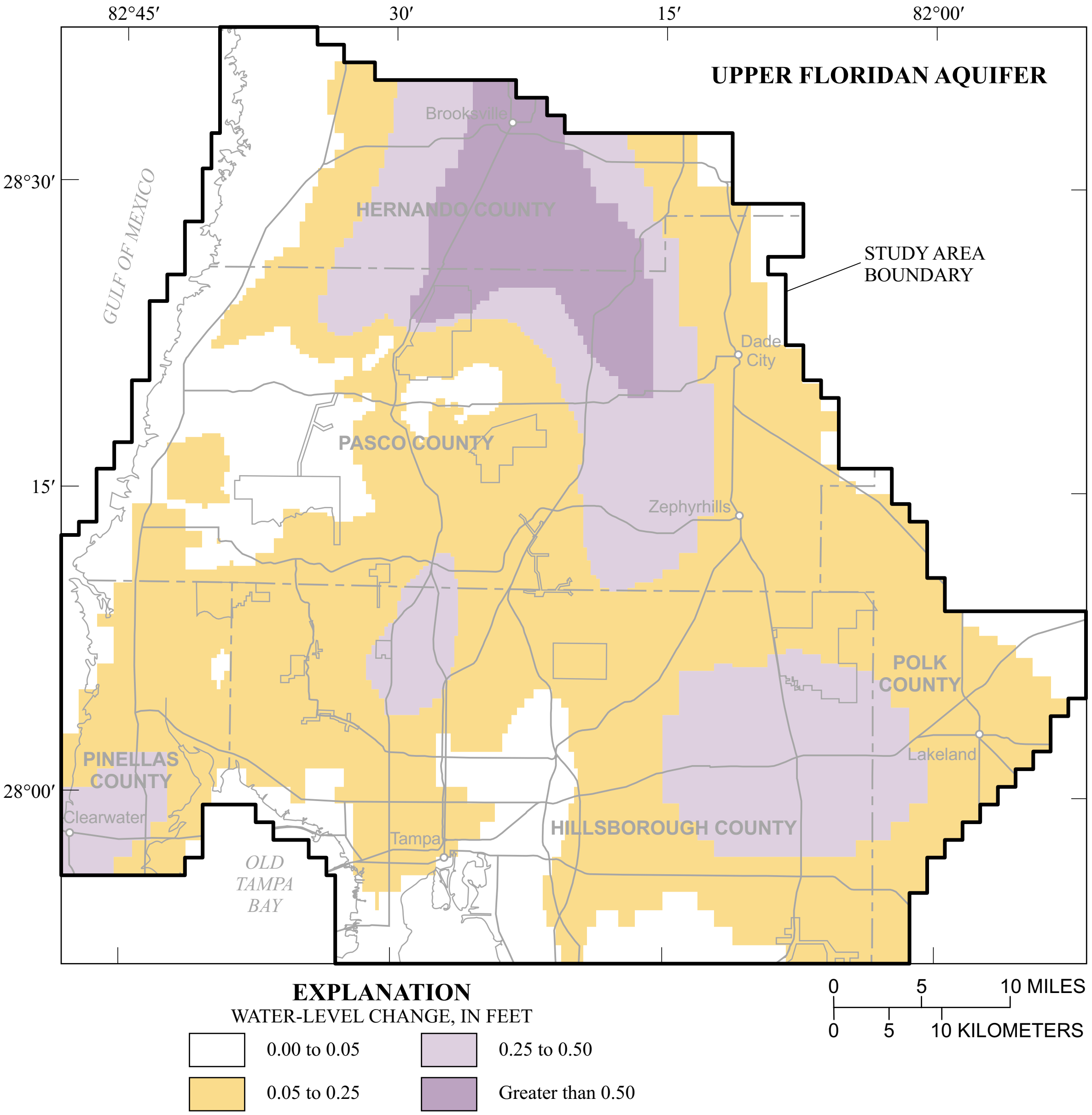


Figure 21B. Sensitivity of simulated water levels to a 2-percent increase in the initial value of recharge.

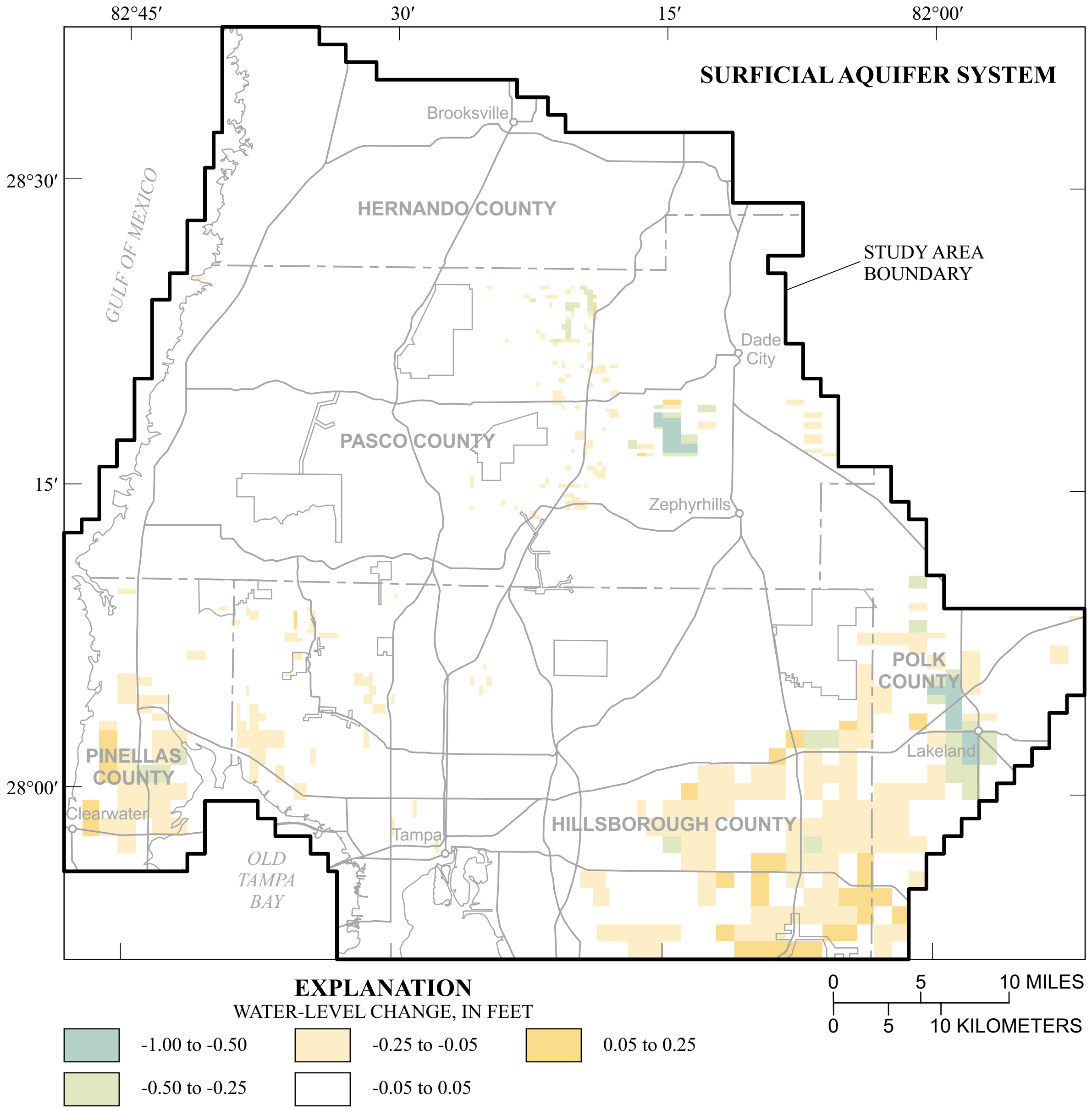


Figure 22A. Sensitivity of simulated water levels to a 2-percent increase in the initial value of hydraulic conductivity of the surficial aquifer system.

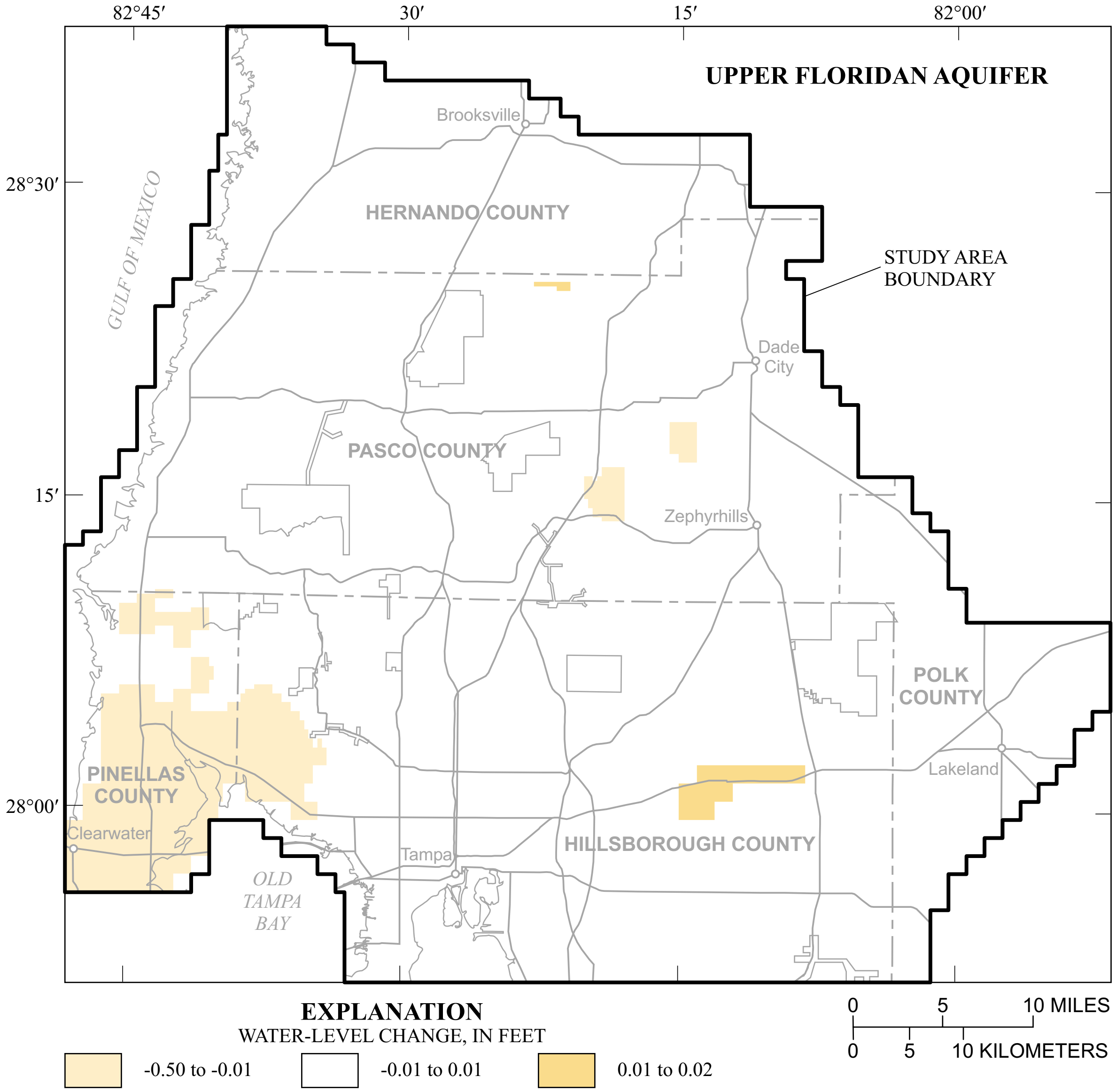


Figure 22B. Sensitivity of simulated water levels to a 2-percent increase in the initial value of hydraulic conductivity of the surficial aquifer system.

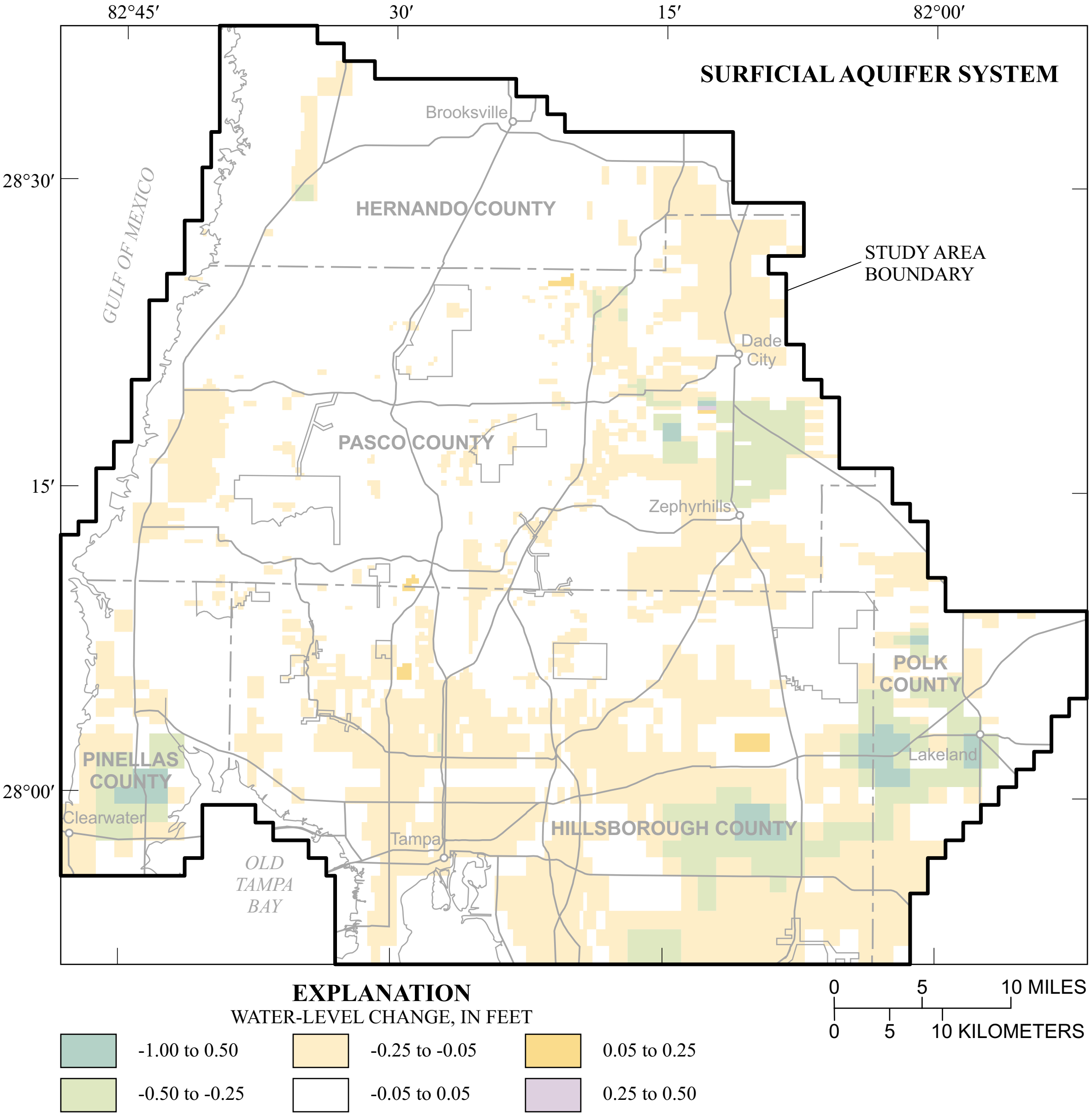


Figure 23A. Sensitivity of simulated water levels to a 2-percent increase in the initial value of leakance.

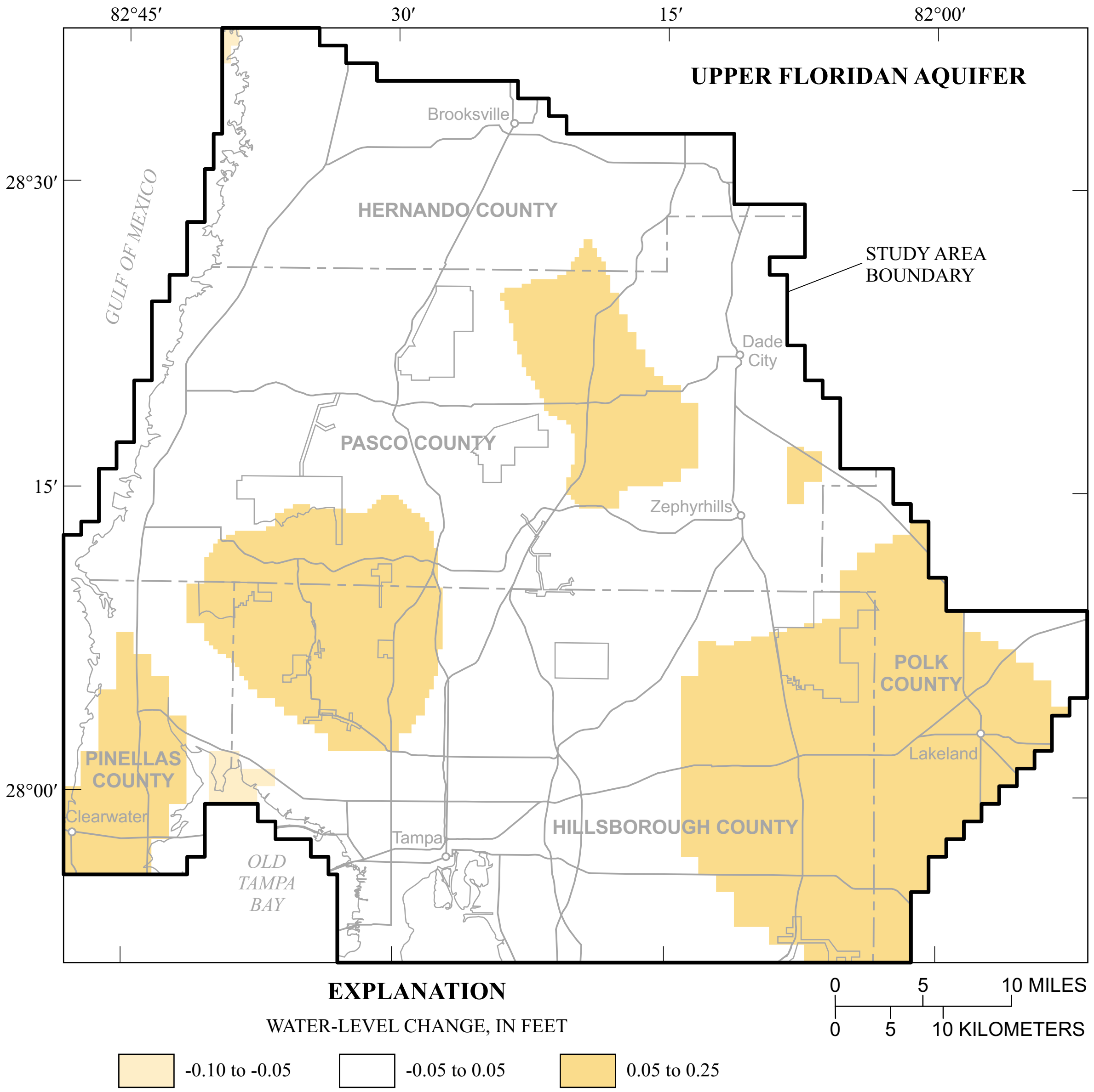


Figure 23B. Sensitivity of simulated water levels to a 2-percent increase in the initial value of leakance.

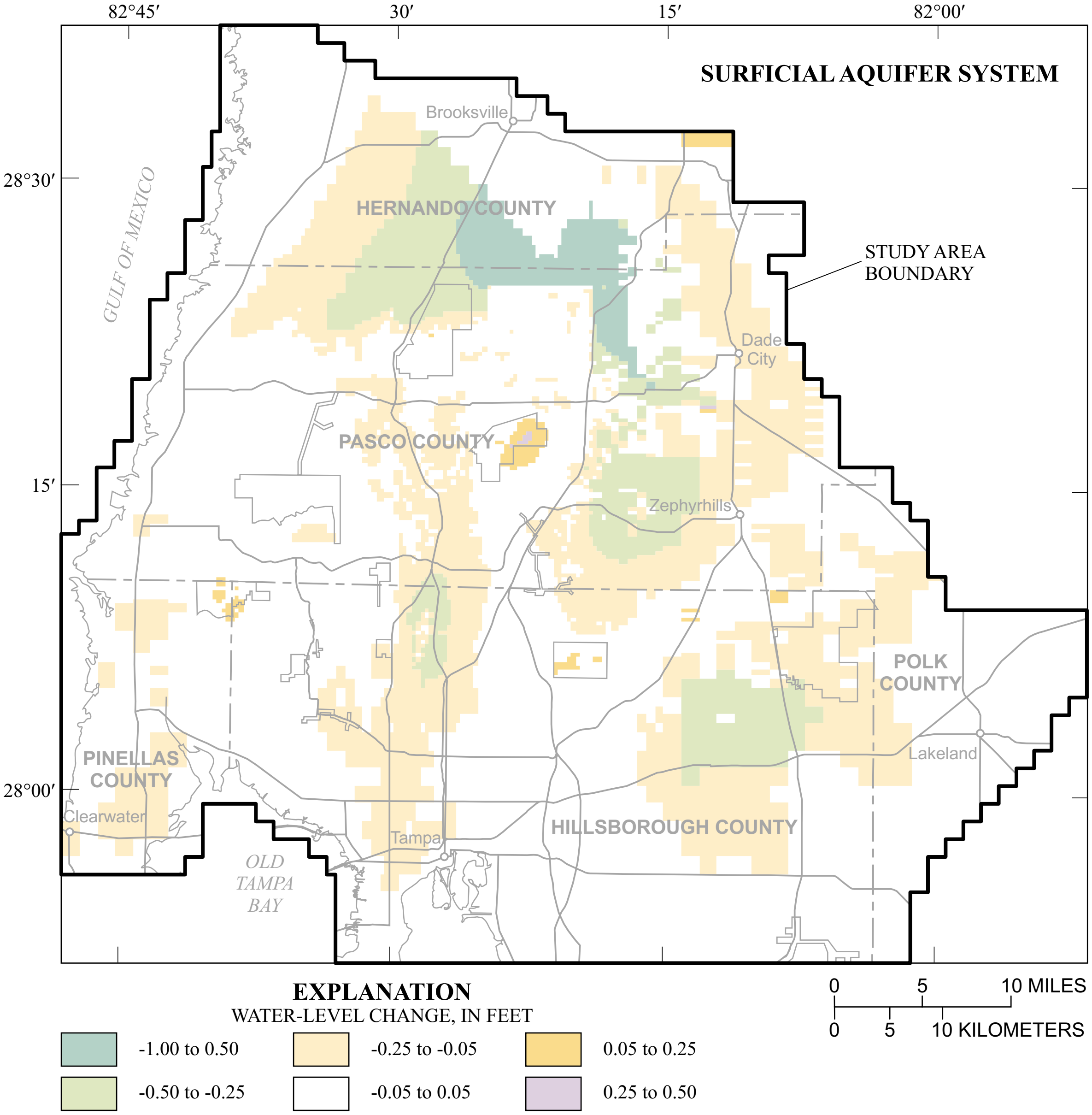


Figure 24A. Sensitivity of simulated water levels to a 2-percent increase in the initial value of Upper Floridan aquifer transmissivity.

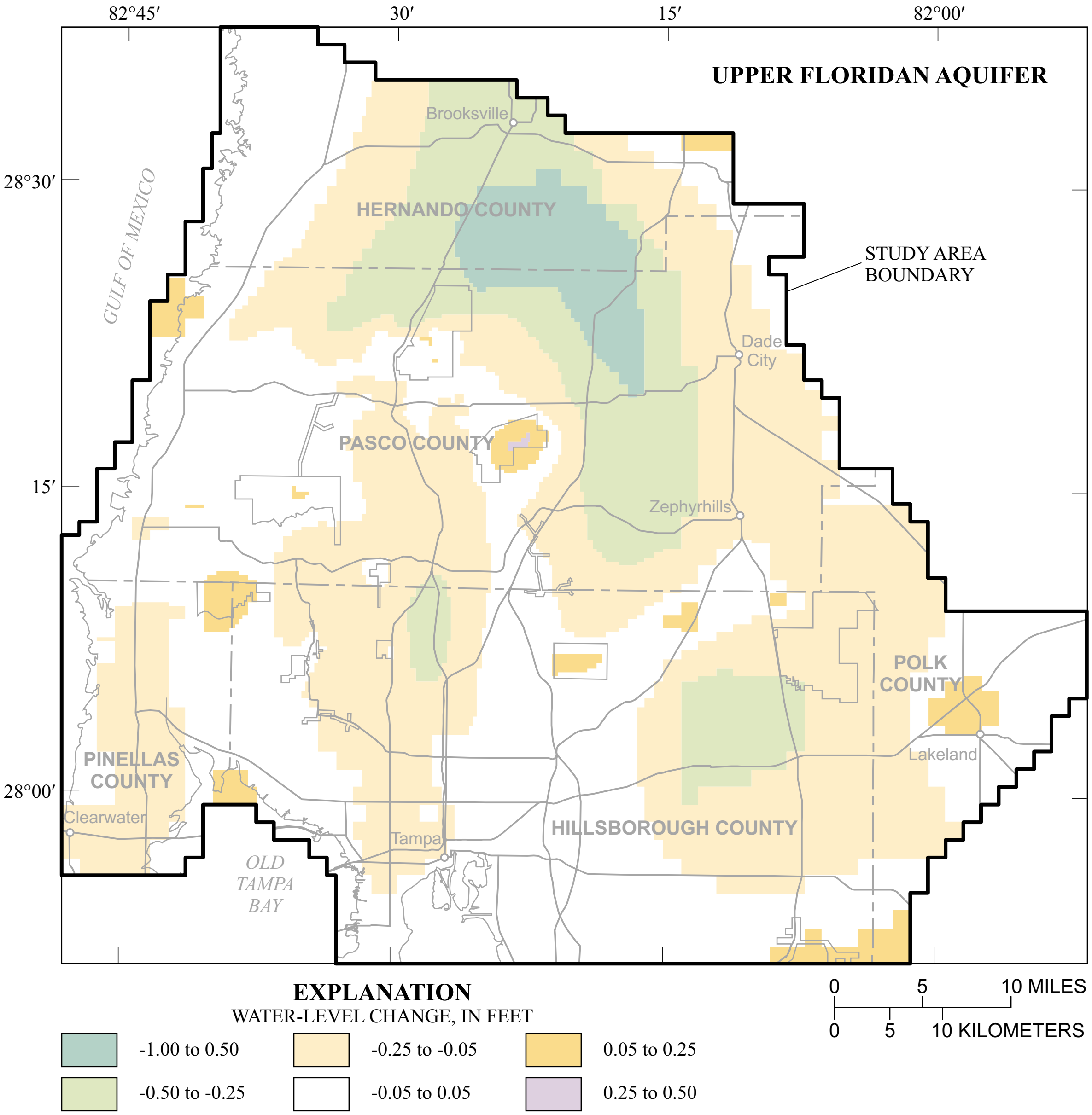


Figure 24B. Sensitivity of simulated water levels to a 2-percent increase in the initial value of Upper Floridan aquifer transmissivity.

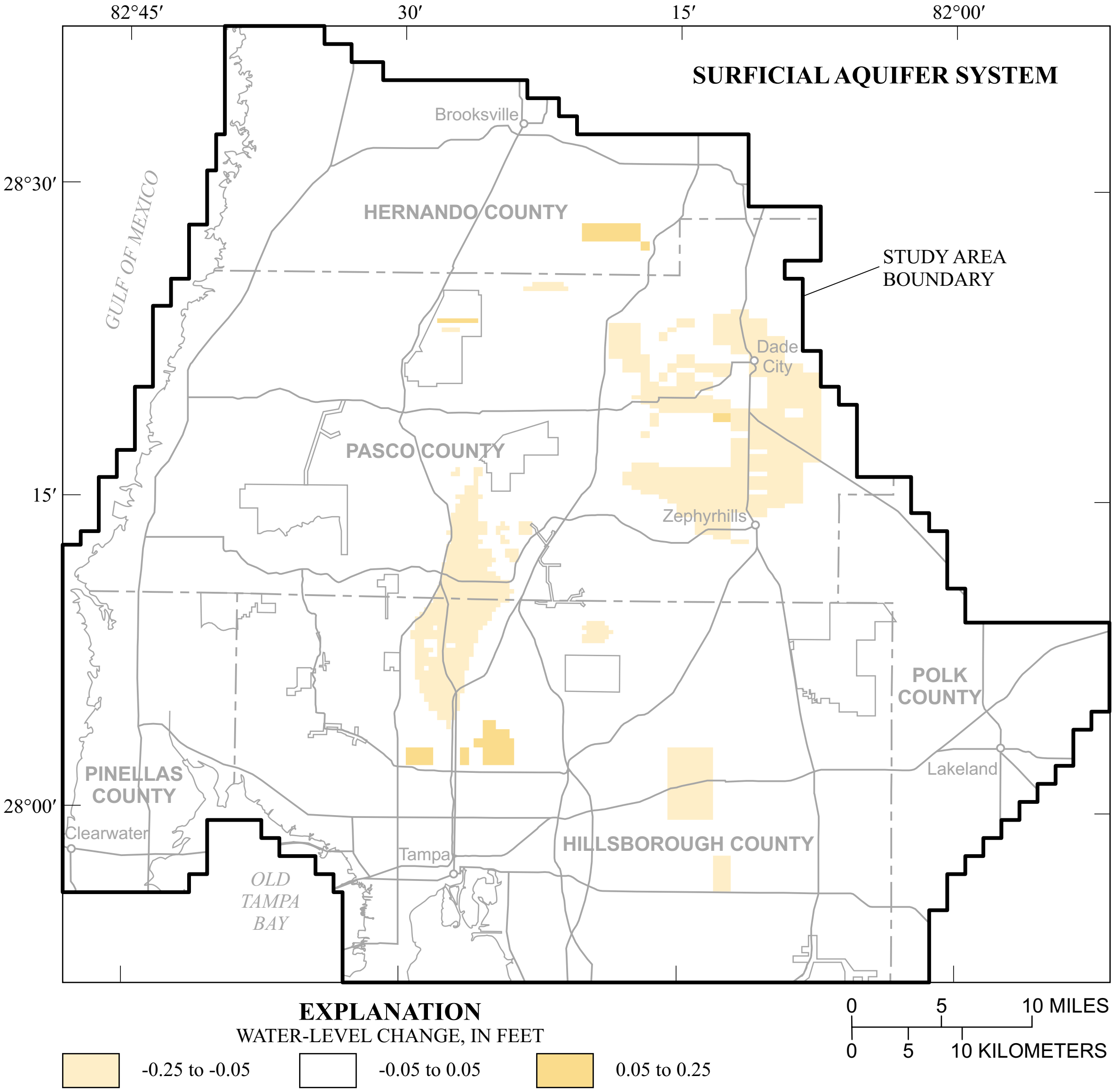


Figure 25A. Sensitivity of simulated water levels to a 2-percent increase in the initial value of Upper Floridan aquifer anisotropy ratio.

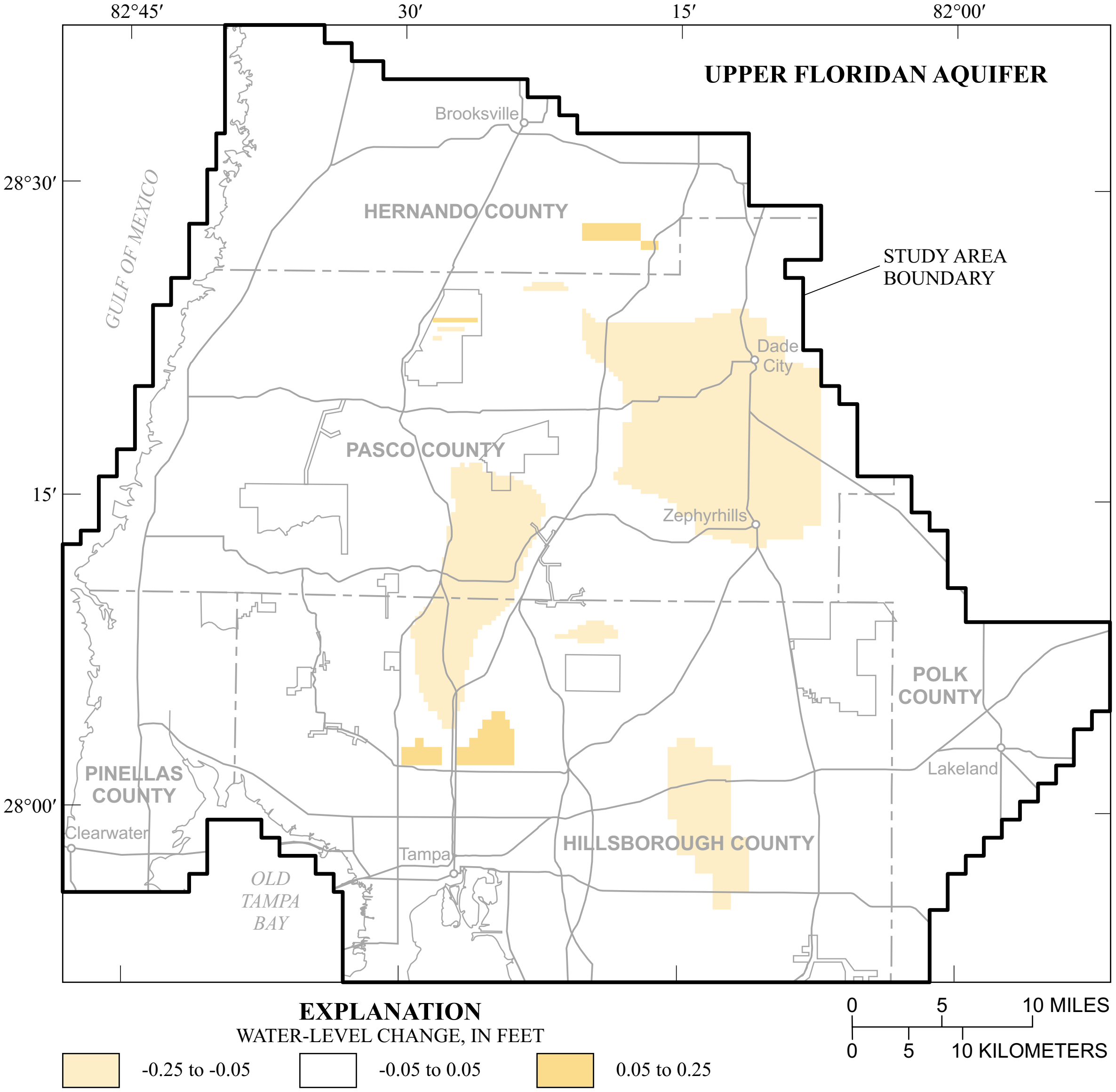


Figure 25B. Sensitivity of simulated water levels to a 2-percent increase in the initial value of Upper Floridan aquifer anisotropy.

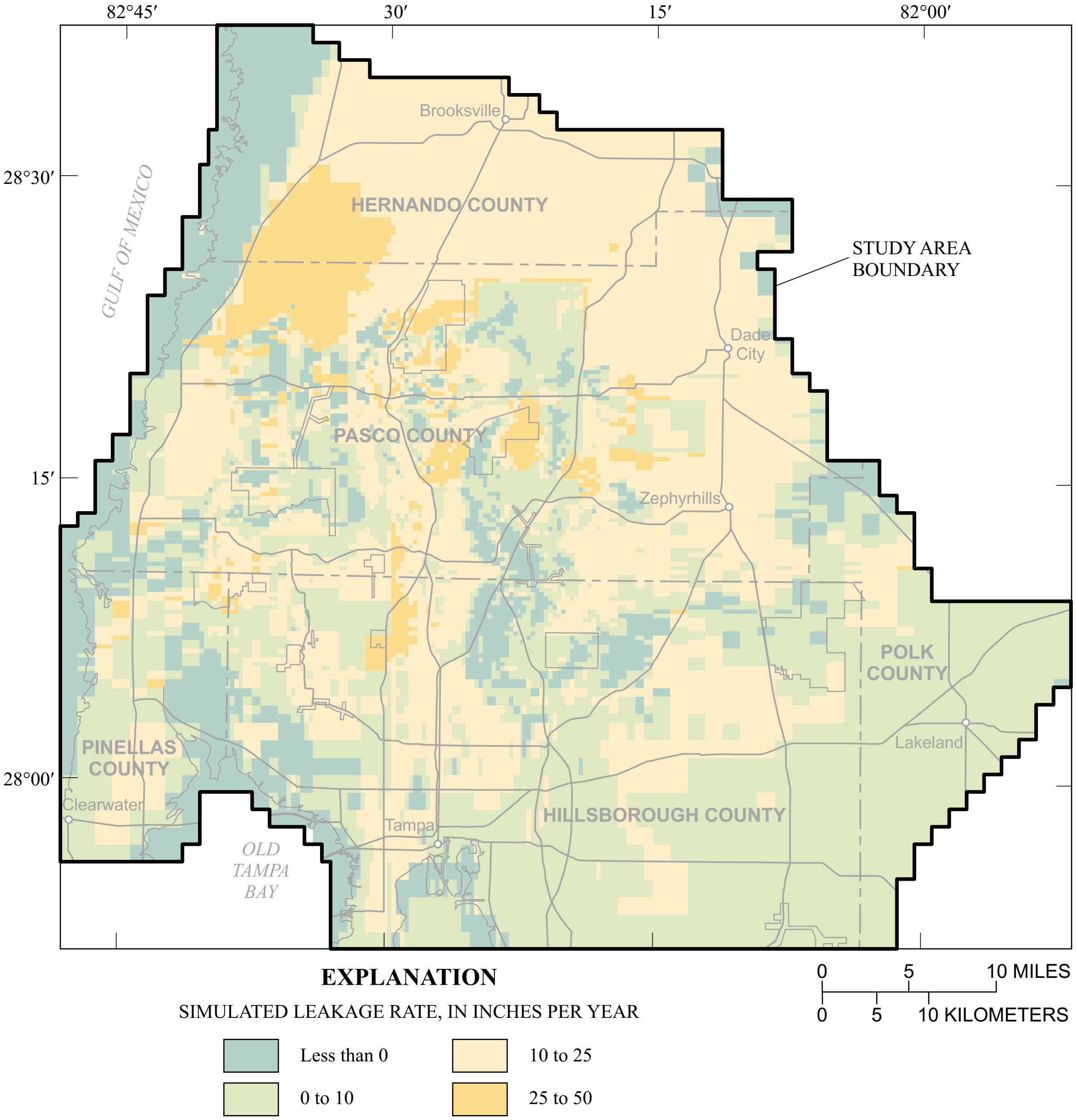


Figure 26. Simulated rate of leakage through the intermediate confining unit based on steady-state 1987 conditions.

not estimated because of low sensitivity of parameter zones and because high correlation was expected between recharge and transmissivity. High correlation was expected because the ground-water flow equation can be written in terms of the ratio (Q = KA(dh/dl)). Unless independent information on recharge or transmissivity is available, the regression cannot be used to distinguish each individual component of the ratio. An incorrectly specified recharge matrix could affect the values, to some degree, and add to the uncertainty in the estimated parameter values.

A total of 23 parameter zones (SDI, 1997) were used to represent transmissivity of the Upper Floridan aquifer. Regression results indicate that the estimate of most transmissivity-zone values is consistent with hydrogeologic information. Generally, values of transmissivity are within 50 percent of the initial values (fig. 27). Optimal estimates of individual transmissivity parameters range from a factor of about 13.9 above to a factor of about 0.1 below the initial values. Several of the values for parameter zones highlighted in figure 27 are probably outside the range of likely values estimated from field data.

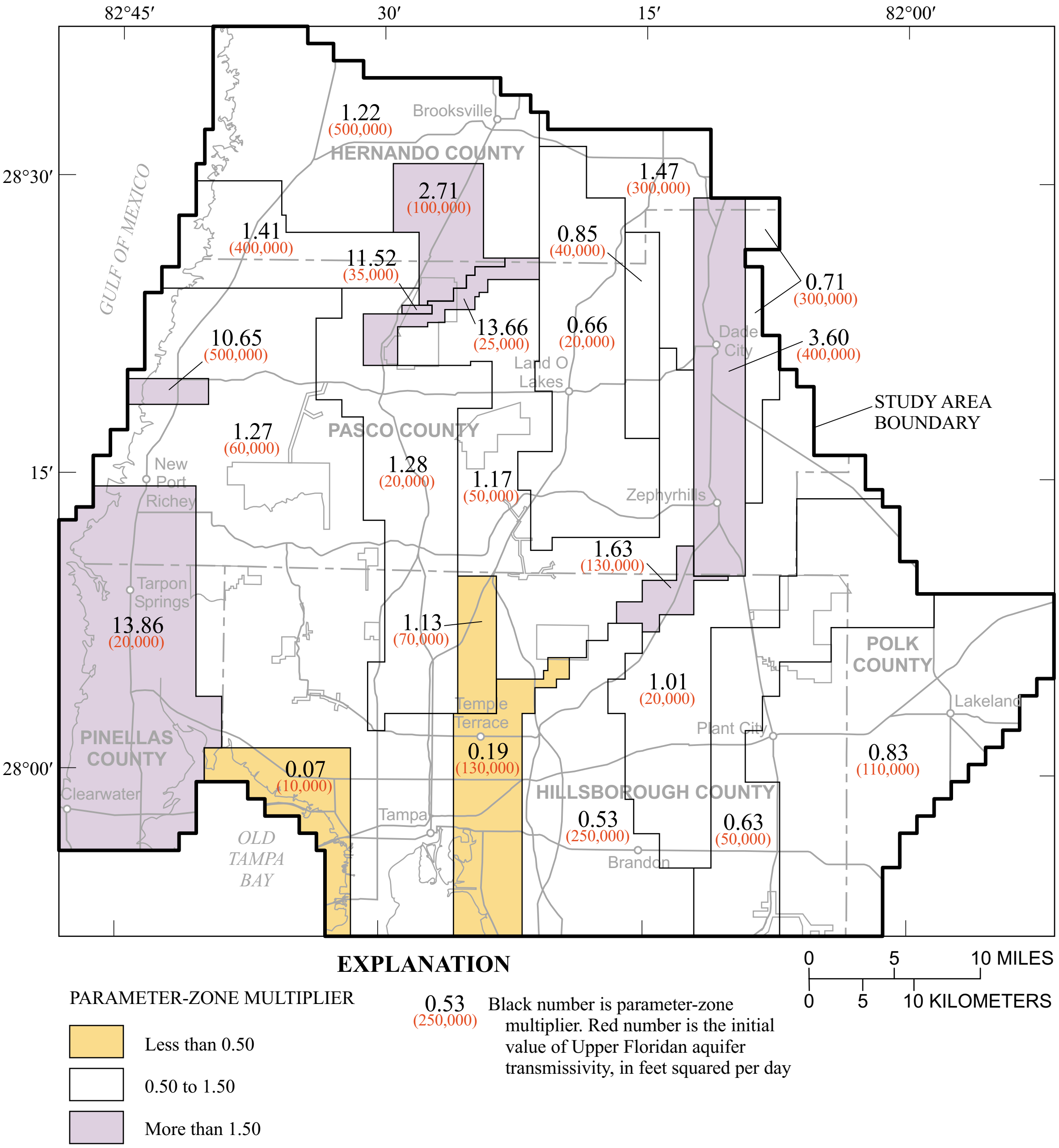


Figure 27. Delineation of Upper Florida aquifer zones used for parameter estimation and simulated transmissivity-zone multiplier for the initial parameter values.

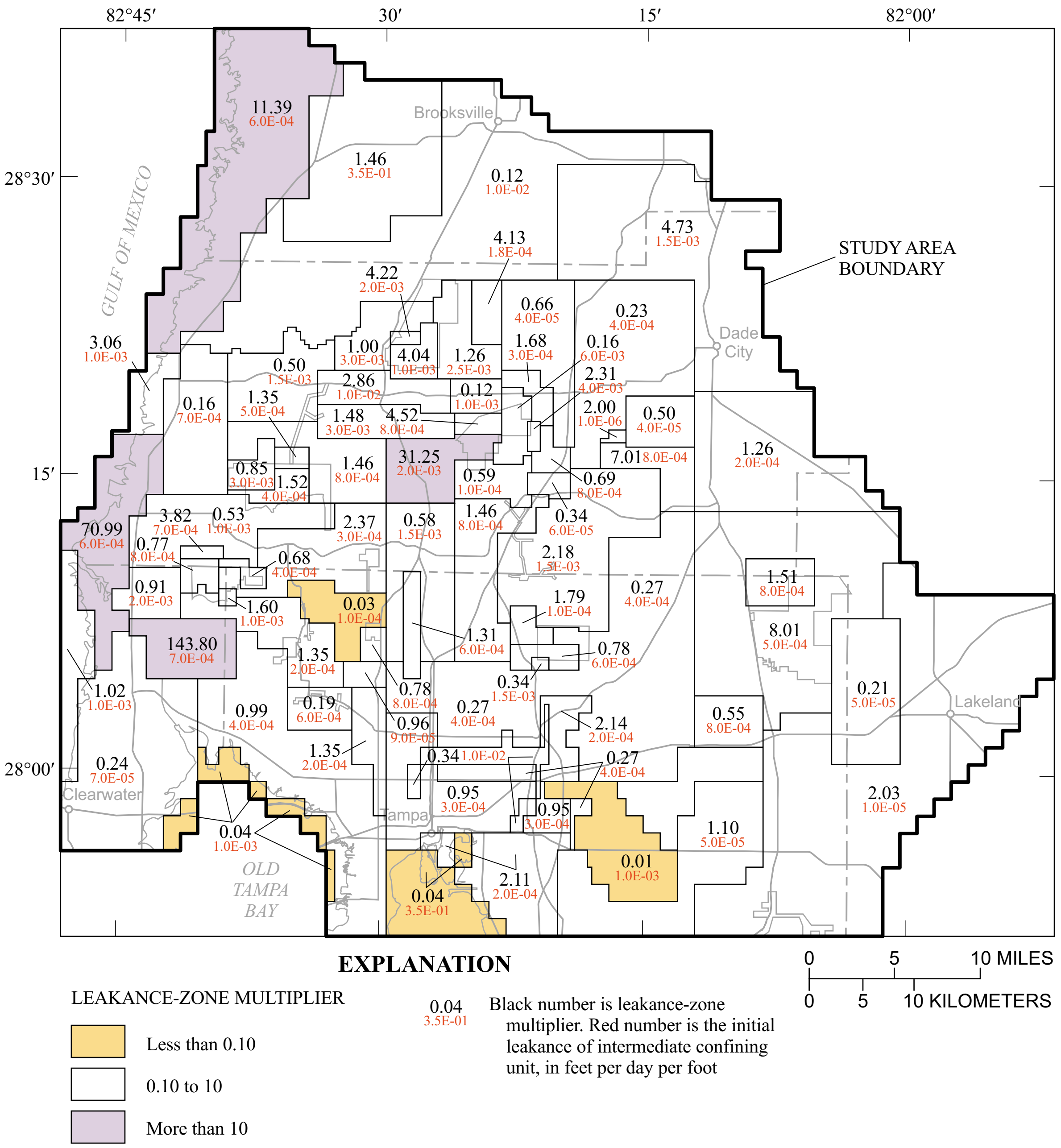


Figure 28. Leakance zones of the intermediate confining unit used for parameter estimation and simulated leakance-zone multiplier for the initial parameter values.

A total of 71 parameter zones (SDI, 1997) were used to represent leakance of the intermediate confining unit. Regression results indicate that the estimate of most leakance parameters is within the expected range of likely values. Generally, values are within an order of magnitude of the initial values (fig. 28). Optimal estimates of individual leakance parameters range from a factor of about 143.8 above to a factor of about 0.01 below initial values. Several of the values for parameter-zones highlighted in figure 28 are probably outside the range of likely values estimated from field data.

One global parameter value served as a multiplier for estimating the spatially variable hydraulic conductivity of the surficial aquifer system. Regression results indicate that the initial estimate of hydraulic conductivity corresponds closely to estimates obtained from other independent sources and is within the range of likely values estimated from field data.

The optimal estimate of hydraulic conductivity is a factor of about 0.78 below the initial values.

One global parameter value served as a multiplier for estimating the spatially variable anisotropy ratio of the Upper Floridan aquifer. Regression results produced an estimated value of anisotropy of the Upper Floridan aquifer within the range of likely values based on very limited field data. The optimal estimate of anisotropy of the Upper Floridan aquifer is a factor of about 0.25 below the initial values.

RCS values for the ninety-six estimated parameter-zone values in the optimized final model are shown in figure 29. The final (optimized) RCS values changed somewhat, but were still quite similar to the initial SDI (1997) parameter values (determined at the first iteration of the optimized simulation). Generally, sensitivity is highest for Upper Floridan aquifer transmissivity zones and lowest for intermediate confining unit zones. As indicated previously, parameters with smaller RCS values relative to those for other parameters are likely to have higher parameter uncertainty; parameters with higher RCS values are likely to have lower parameter uncertainty.

Most of the estimated parameters are not highly correlated to one another, as indicated by small correlation coefficients (most less than 0.50, appendix). The most highly correlated pair is adjacent leakance zones 47 and 25 (appendix) with a correlation coefficient of –0.99. The second highest correlated pair is adjacent leakance zones 13 and 22 with a correlation coefficient of –0.88.

The effects using a different set of water-level observations also were evaluated. Comparisons were made between an inverse model with the 119 calibration water-level observations used in the SDI (1997) model calibration and the present inverse model which uses 549 water-level observations. Simulated parameter-zone multipliers derived from the two data sets are presented in figure 30 and a statistical

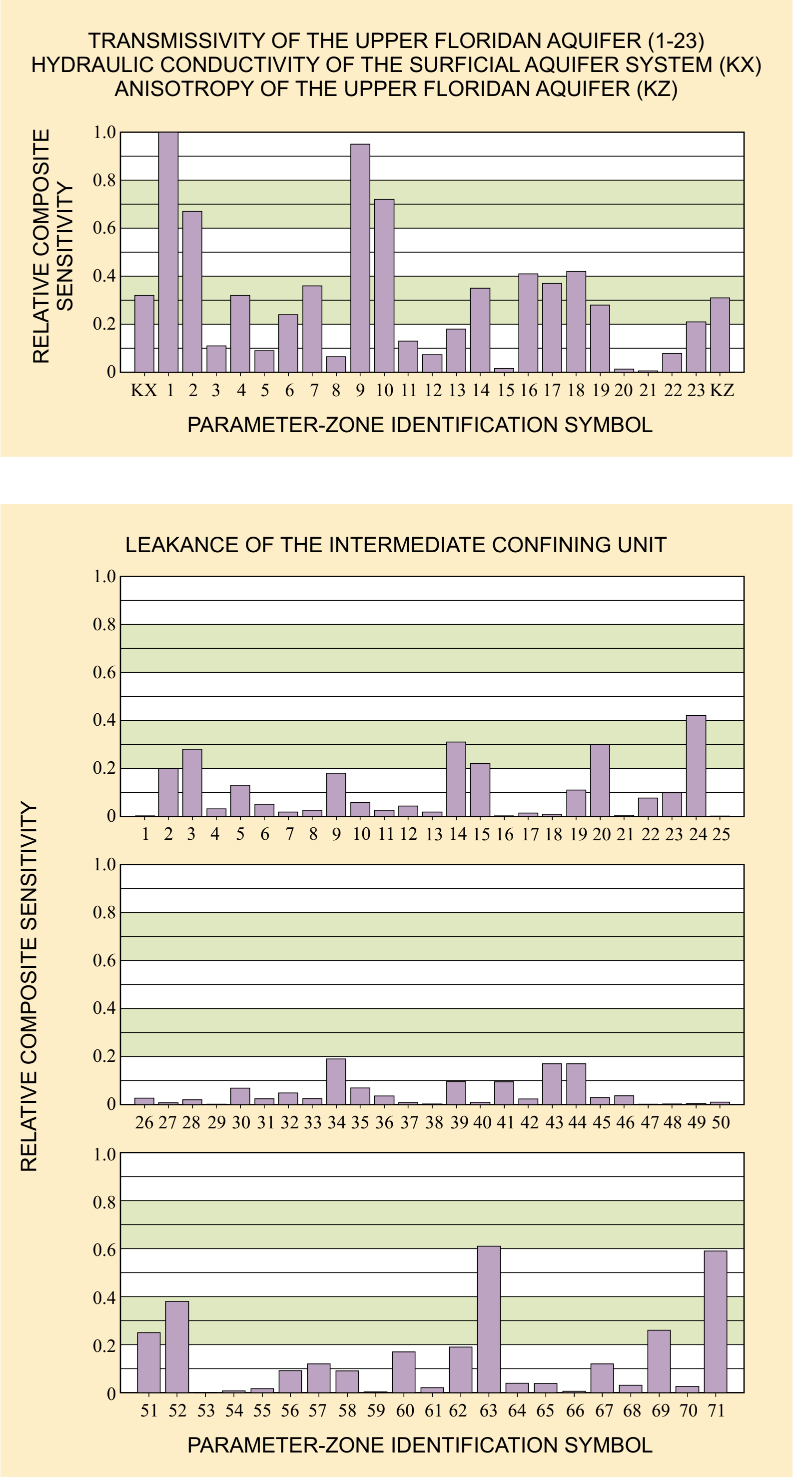


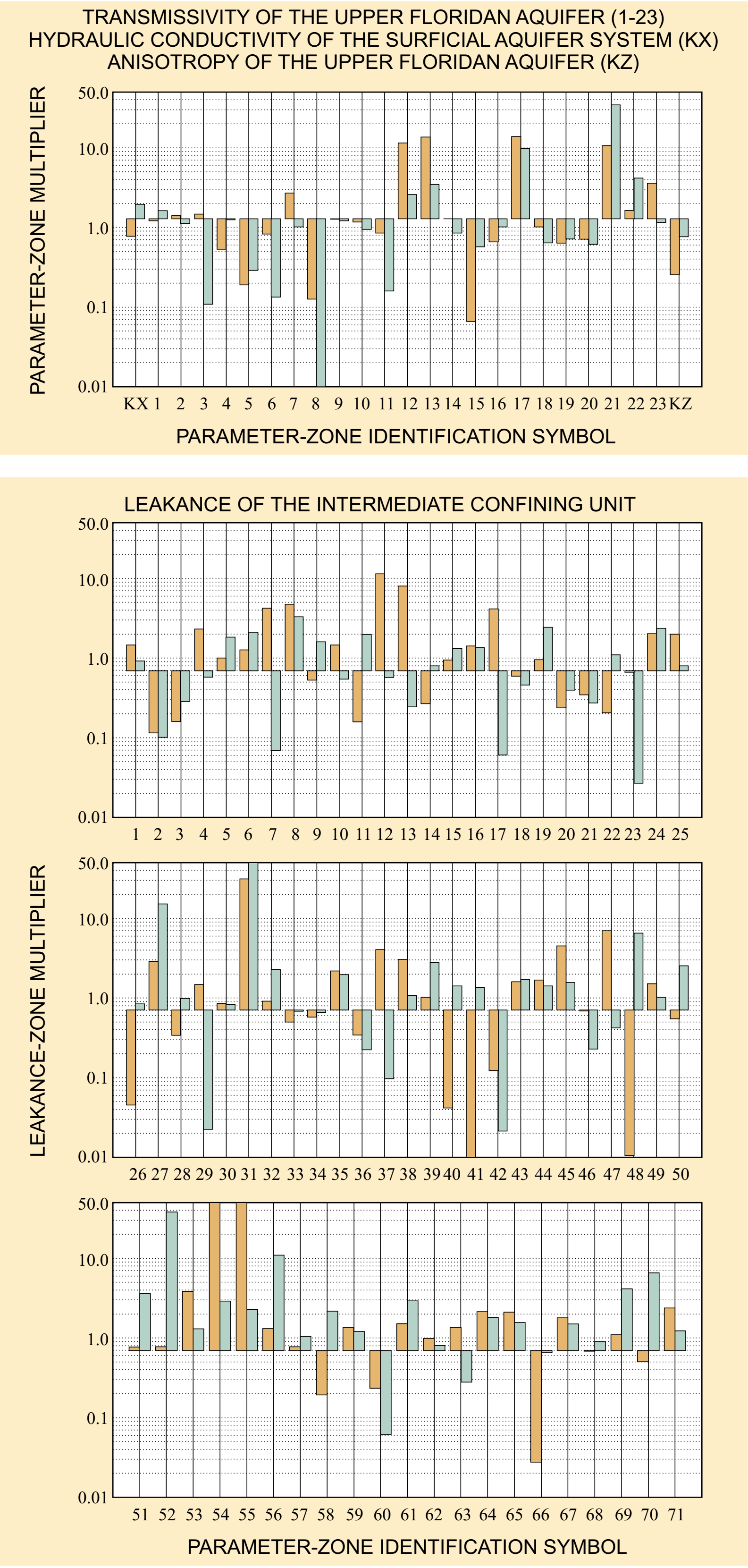
Figure 29. Relative composite sensitivity for optimal estimates of input parameter values.

summary of the results is presented in table 6. Most of the statistics shown in table 6 and many of the optimized values shown in figure 30 are significantly different for the two data sets. These differences reflect the dependency of inverse model results on the parameter-zonation structure and the observation data set. Inverse model instability occurs when too many parameters are estimated based on a limited number of observations.

Model Agreement

Model fit of the parameter-estimation model was evaluated both objectively and subjectively. A statistical analysis of residuals (simulated values minus measured values) was used to objectively assess the overall goodness of model fit. Residuals are important indicators of model fit, but are dependent on both the quality of observation data and model accuracy. The quantities included in the evaluation are: (1) water levels; (2) river base flows; and (3) spring flows. Inspection of the spatial distribution of errors of water level, direction and magnitude of ground-water flow, and river and spring discharges were used to subjectively analyze model performance.

Observation data available for comparison with simulated values included 549 measured water levels in wells completed in the surficial aquifer system and the Upper Floridan aquifer, 15 estimated river base flows, and 23 measured spring flows. However, only the 549 hydraulic water-level values were used in the inverse model.



EXPLANATION

🟩 OPTIMIZED VALUES USING 119 WATER-LEVEL OBSERVATIONS

🟧 OPTIMIZED VALUES USING 549 WATER-LEVEL OBSERVATIONS

Figure 30. Simulated parameter-zone multipliers derived from two separate sets of water-level observations.

Table 6. Statistical summary of optimal parameter-zone multipliers derived from 119 and 549 water-level observations

[UFA, Upper Florida aquifer; ICU, intermediate confining unit; K, hydraulic conductivity; Kx/Ky, horizontal anisotropy ratio; SAS, surficial aquifer system]

Statistic	Transmissivity of the UFA		Leakance of the ICU		K of the SAS		Kx/Ky of the UFA	
	119	549	119	549	119	549	119	549
Number of zones	23	23	71	71	1	1	1	1
Minimum	0.01	0.07	0.02	0.01				
Maximum	34.58	13.86	490.50	143.80				
Mean	2.96	3.09	9.12	5.02	1.96	0.78	0.77	0.25
Standard deviation	7.29	4.49	58.15	19.03				

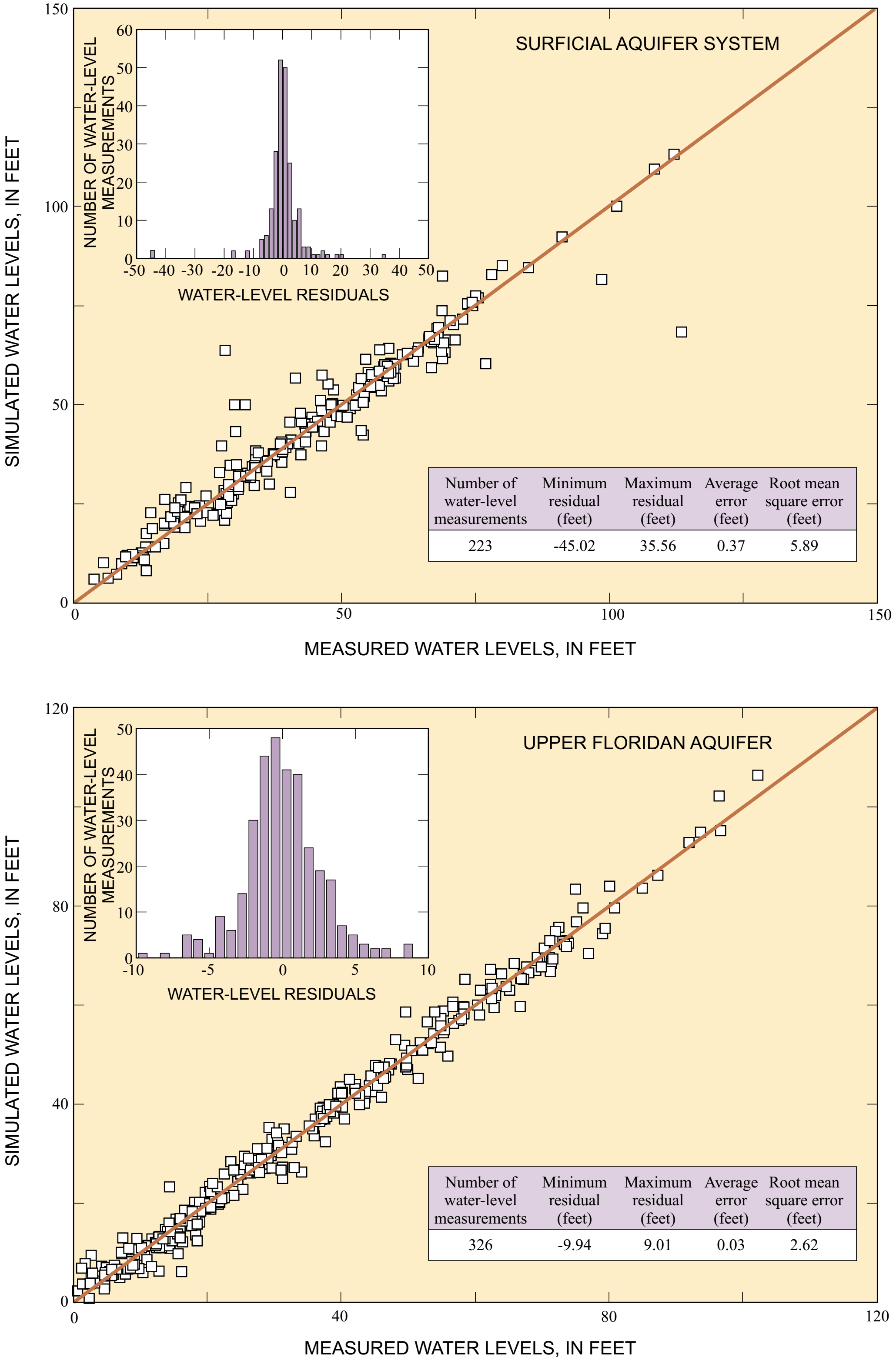
The parameter-estimation model generally produced simulated water levels in close agreement with measured water levels (table 7 and fig. 31). The water-level residuals were normally distributed; approximately 70 percent of the simulated water levels are within 2 ft of the measured water levels and approximately 90 percent are within 5 ft of measured levels. The residual statistics show that the overall model fit for both layers is improved when parameters are optimized using nonlinear regression. The RMSE was reduced from 7.35 to 5.63 ft and the average residual was reduced from 0.37 to 0.09 ft (fig. 32 and table 7). The small improvement relative to the overall error is primarily due to large surficial aquifer system residuals in both models and the bias of the SS to well field areas where dense clusters of wells are present.

Simulated water-table altitudes for the surficial aquifer system are shown in figure 33. The flow model simulated average annual steady-state water levels for the period January through December 1987. Simulated water levels were slightly higher than measured water levels; the average difference between simulated and measured water levels at 223 measurement sites was 0.37 ft. The general directions of simulated ground-water flow and the magnitude of hydraulic gradients within the surficial aquifer system were in close agreement with measured water levels. There are a few notable exceptions to this agreement where model results may be deficient. For example, in a small area of Hernando and Pasco County, south of Brooksville and north of Dade City, the surficial aquifer system cells go dry and the model does not simulate the water table accurately. This is in an area where the Upper Floridan aquifer is unconfined and where hydraulic separation between the surficial aquifer system and the Upper Floridan aquifer does not exist (SDI, 1997).

In cells that go dry (Brooksville area), the altitude of the water-table surface in the surficial aquifer system is assumed to be equal to the altitude of the potentiometric surface in the Upper Floridan aquifer. Also in the Brandon and Clearwater areas, the model does not simulate water levels accurately (residuals

Table 7. Statistical summary of differences between simulated and measured water levels for the initial and optimized simulations

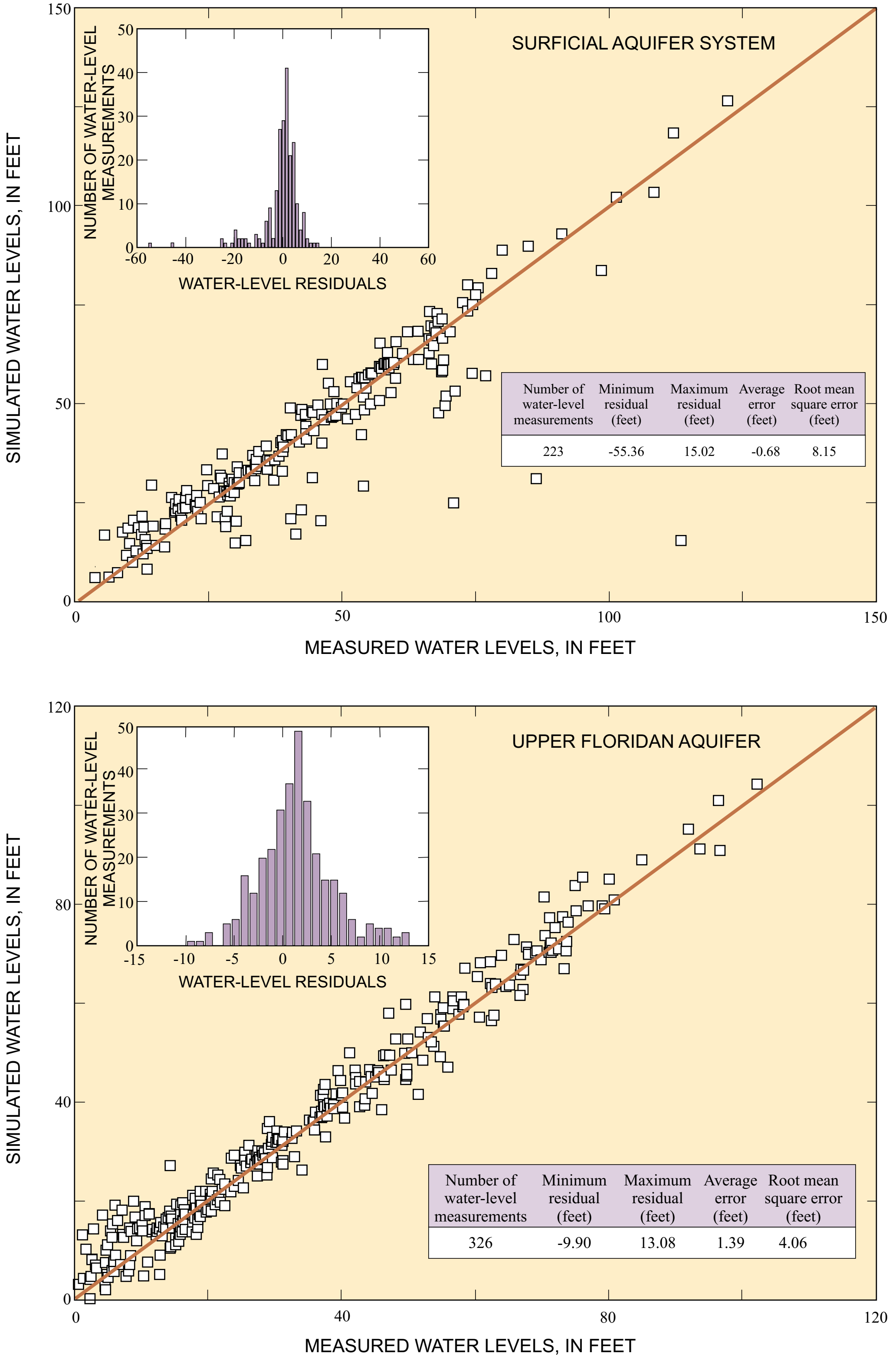
	Number of observations	Root mean square error (feet)	Average water-level residuals (feet)	Minimum water-level residuals (feet)	Maximum water-level residuals (feet)
Surficial aquifer system					
Initial values	223	8.15	-0.67	-55.36	15.02
Optimized values	223	5.89	0.37	-45.02	35.56
Upper Floridan aquifer					
Initial values	326	4.06	1.39	-9.90	13.08
Optimized values	326	2.62	0.03	-9.94	9.01
Entire model					
Initial values	549	7.35	0.37	-55.36	15.02
Optimized values	549	5.63	0.09	-45.02	35.56



Number of water-level measurements	Minimum residual (feet)	Maximum residual (feet)	Average error (feet)	Root mean square error (feet)
223	-45.02	35.56	0.37	5.89

Number of water-level measurements	Minimum residual (feet)	Maximum residual (feet)	Average error (feet)	Root mean square error (feet)
326	-9.94	9.01	0.03	2.62

Figure 31. Comparison of simulated to measured water levels for the parameter-estimation model.



Number of water-level measurements	Minimum residual (feet)	Maximum residual (feet)	Average error (feet)	Root mean square error (feet)
223	-55.36	15.02	-0.68	8.15

Number of water-level measurements	Minimum residual (feet)	Maximum residual (feet)	Average error (feet)	Root mean square error (feet)
326	-9.90	13.08	1.39	4.06

Figure 32. Comparison of simulated to measured water levels for the initial central northern Tampa Bay area hydrologic model.

greater than 10 ft below measured). In the Brandon and Clearwater areas, measured water levels may represent local or perched water-level conditions that cannot be simulated due to the localized nature of the perched system. The residuals also could indicate that either recharge rate in these areas was underestimated or the leakance of the intermediate confining unit between layers was overestimated. No spatial trends in the distribution of water-level residuals are apparent (fig. 33).

The simulated potentiometric surface of the Upper Floridan aquifer is shown in figure 34. Simulated water levels were slightly higher than measured water levels; the average difference between simulated and measured water levels at the 326 measurement sites was 0.03 ft. The magnitude and direction of simulated hydraulic gradients are similar to measured water levels. No spatial trends in the distribution of water-level residuals are apparent (fig. 34).

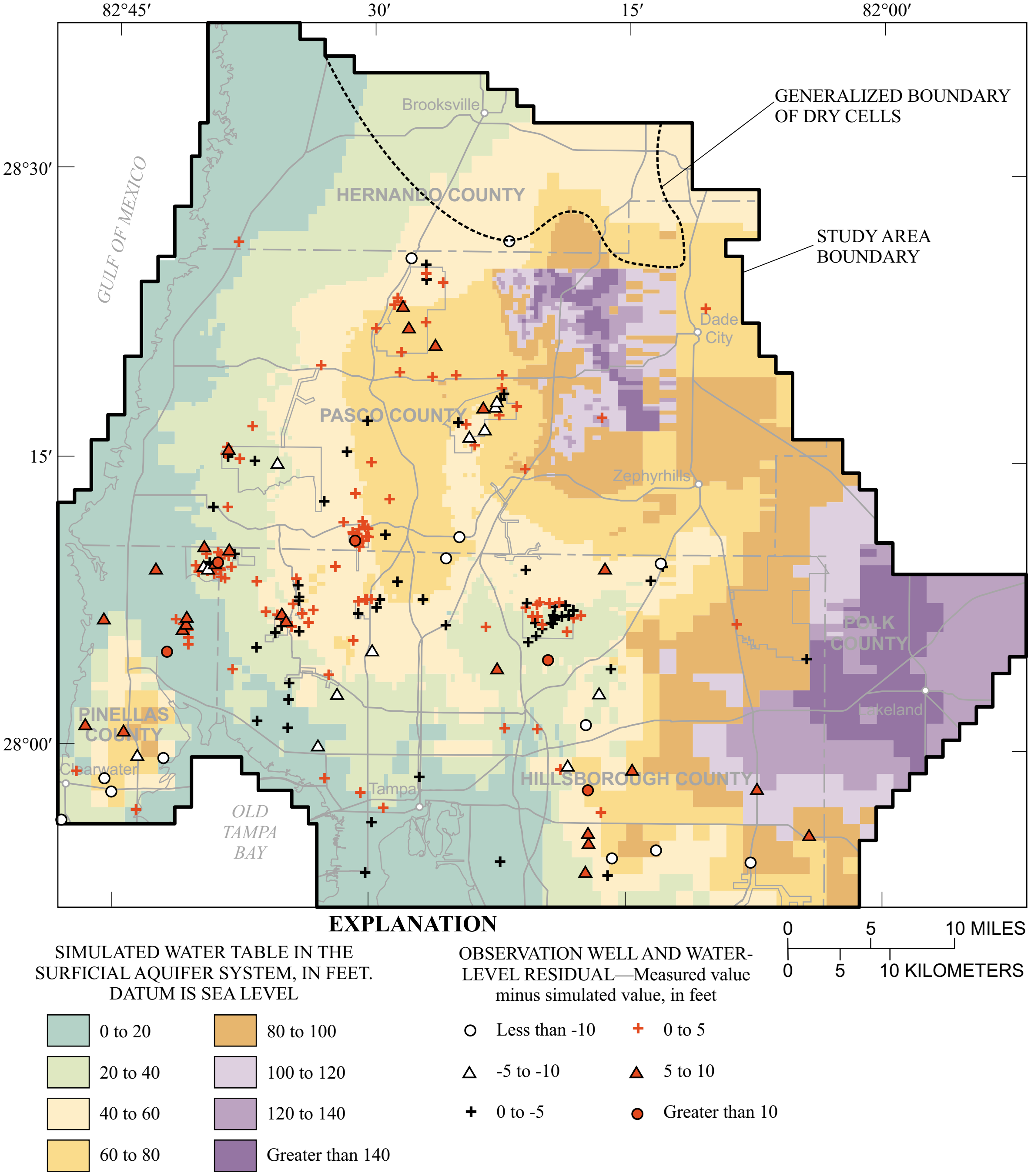


Figure 33. Location of water-level measurements, value of water-level residuals, and simulated water table in the surficial aquifer system, calendar year 1987.

Simulated river base flow was compared at 21 sites (table 8). The simulated annual average ground-water discharge to streams was simulated as 84 ft^3/s for the 1987 calendar year. Base flow, determined by hydrograph separation techniques using a computerized program (White and Sloto, 1991), was estimated to be 557 ft^3/s. The simulated discharge compares poorly with the estimated discharge, probably due to the scale of the model. A greater level of detail in river-bed leakance, stage, and bottom elevation, which is consistent at all scales, should be incorporated into this model to more accurately simulate base flow rates.

Simulated spring flow was compared at 13 sites (table 9). The simulated annual average ground-water discharge to springs was estimated to be 392 ft^3/s for the 1987 calendar year. Total spring flow, determined from direct measurements and estimates was about

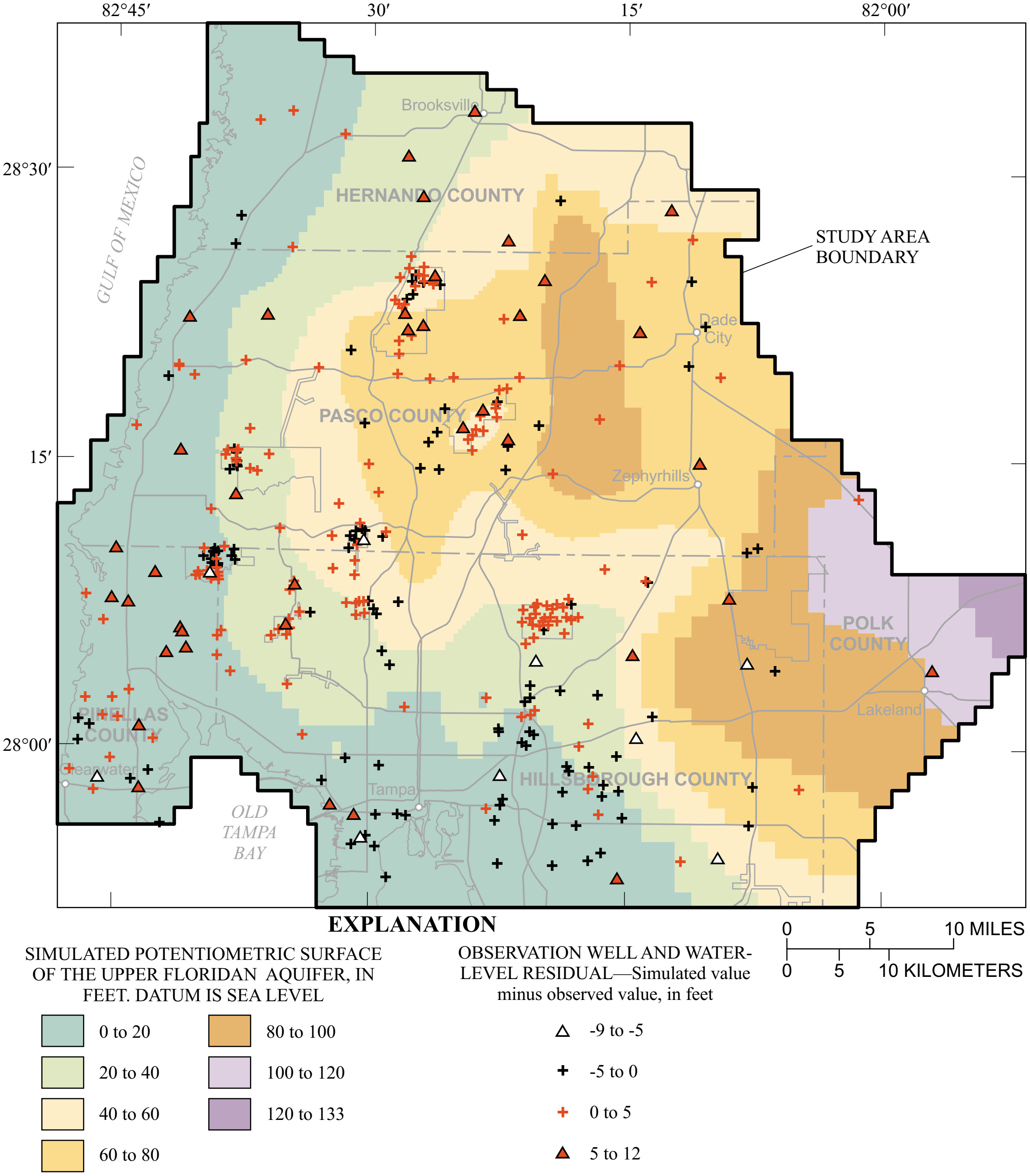


Figure 34. Location of water-level measurements, value of water-level residuals, and simulated potentiometric surface of the Upper Floridan aquifer, calendar year 1987.

Table 8. Comparison of model-simulated and estimated base flows, calendar year 1987

[ft^3/s; cubic foot per second]

Station name	Station number	Estimated base flow (ft^3/s)	Maximum discharge (ft^3/s)	Minimum discharge (ft^3/s)	Average discharge (ft^3/s)	Optimized base flow (ft^3/s)
Anclote River:						
South Branch near Odessa	02309848	1.8	184	0.01	5.33	0.5
Near Odessa	02309980	22.7	1,840	0.85	78.6	4.1
Near Elfers	02310000	26.5	82.9	3.60	82.9	4.6
Brooker Creek:						
At Van Dyke	02307200	2.0	97.0	0.01	5.45	0.9
Near Lake Fern	02307323	2.5	153	0.01	9.05	0.8
Near Lake Tarpon	02307359	9.2	434	0.42	21.8	0.8
Hillsborough River:						
Near Zephyrhills	02303000	60.1[1]	3,980	83.0	220	24.2
At Morris Bridge	02303330	105.7[1]	3,160	92.0	270	7.6
Near Tampa	02304500	151.8[2]	3,020	0.26	359.06	10.6
Hillsborough River Tributaries:						
Blackwater Creek near Knights	02302500	17.0	1,760	4.50	67.0	0.2
Cypress Creek						
Near San Antonio	02303400	8.6	996	0.12	25.46	0.2
At Worthington Gardens	02303420	20.1	1,430	0.72	73.54	4.5
Near Sulphur Springs	02303800	41.9	1,430	2.40	104	5.6
Flint Creek near Thonotosassa	02303300	16.1	322	2.00	43.2	1.1
Trout Creek near Sulphur Springs	02303350	3.5	30.8	0.00	30.8	2.6
Pithlachascotee River:						
Near Fivay Junction	02310280	4.5	130	0.41	11.7	4.6
Near New Port Richey	02310300	10.7	879	0.91	33.5	6.0
Rocky Creek:						
At State Highway 587	02306774	7.5	195	0.85	15.0	0.1
Near Sulphur Springs	02307000	32.1	724	4.50	66.8	2.3
Rocky Creek Tributaries:						
Brushy Creek near Tampa	02303910	10.0	259	2.90	21.2	0.3
Sweetwater Creek near Tampa	02306647	3.1	310	1.40	25.2	2.4
Totals		557.4				84.0

[1] Crystal Springs discharge excluded

[2] Includes surface withdrawals of 85 ft^3/s for the City of Tampa

Table 9. Comparison of model-simulated and measured spring flows, calendar year 1987

[ft^3/s, cubic foot per second]

Spring name	Measured or estimated flow (ft^3/s)	Optimized flow (ft^3/s)
Buckhorn	9.4	10.3
Crystal	54.7	76.8
Gator, Bobhill, Magnolia	6.8	0.0
Heath	6.5	24.5
Horeshoe	8.6	0.9
Hudson	30.0	1.4
Lettuce, Eureka	11.0	0.0
Lithia	44.5	23.9
Salt (Pasco)	9.5	10.3
Salt, Mud	27.2	0.0
Shady	0.4	1.6
Sulphur	38.2	31.9
Weeki Wachee	185	210.9
Totals	431.8	392.5

432 ft^3/s. Total simulated spring flow compares favorably with total measured spring flow; however, the simulated spring flow for individual springs compares poorly with the measured and estimated discharge. Matching individual spring flows is difficult and also is of questionable value because of discretization and data input problems. Many individual springs have been assigned to multiple grid cells instead of single grid cells; including Weeki Wachee, Lithia, Gator, Bobhill, Magnolia Springs, and Salt Springs. In addition, many of the spring altitudes were determined from topographic maps resulting in estimated spring-pool altitudes that affect simulated flow. Spring-pool altitudes assigned to the cell containing Salt and Mud Springs (7 ft above sea level), and the cells containing Gator, Bobhill, and Magnolia Springs (13 ft above sea level) are set too high, and therefore, flow from these springs is reduced.

Components of the simulated hydrologic budget of the modeled area for the 1987 calendar year are shown in table 10. Of the 15.3 in/yr of flow through the surficial aquifer system and the Upper Floridan aquifer (sum of inflows or outflows shown in bold in table 10), nearly 90 percent consists of recharge from rainfall to the surficial aquifer system. In addition, simulated net leakage to the Upper Floridan aquifer from the surficial aquifer system was 7.2 in/yr, which represents 46 and 67 percent of the total flows in the surficial aquifer system and the Upper Floridan aquifer, respectively.

Limitations of Model Analysis

This inverse model, or any other model, is limited by simplification of the conceptual model, discretization effects, difficulty in obtaining sufficient measurements to account for all of the spatial variation in hydraulic properties throughout the model area, and limitations in the accuracy of land surface altitude measurements. The inverse model simulates average annual conditions and does not account for seasonal changes in ground-water recharge and discharge or seasonal variability in values of hydraulic head. The model yields parameter-zone values similar to estimates from field data and produces simulated water levels in close agreement with measured water levels. This model, however, is not unique, and different ground-water flow model constructions with optimal parameter estimates may fit the available observations equally well. Results showed that there are not

Table 10. Simulated hydrologic budget of the aquifer system in the study area, calendar year 1987

[All values are fluxes averaged over the model area. Sum of bold number represent total inflow or outflow through Upper Florida aquifer (UFA) and the surficial aquifer system (SAS)]

Budget component	Inflow (inches per year)	Outflow (inches per year)
SURFICIAL AQUIFER SYSTEM		
Recharge from rainfall	**13.6**	
Upward Leakage from UFA	2.0	
Downward leakage to UFA		9.2
Rejected recharge (drains)		**3.8**
Discharge to rivers		**1.7**
Discharge to coast		**0.9**
Pumpage from wells		< 0.01
Total flow	15.6	15.6
UPPER FLORIDAN AQUIFER		
Leakage from SAS	9.2	
Direct recharge from rainfall	**1.2**	
Specified head boundary	**0.3**	
Leakage from rivers	**0.2**	
Discharge to springs		**3.3**
Pumpage from wells		**2.9**
Upward leakage to SAS		2.0
Discharge to rivers		**1.8**
General head boundary		**0.6**
Discharge to Bear Sink and Round Sink		**0.3**
Total flow	10.9	10.9

sufficient water-level data to independently estimate all possible parameters. In addition, several parameter values estimated by the regression are probably not reasonable. The inverse model is designed not as a predictive tool, but as an interpretive one; it is intended to gain modeling insight given the proposed conceptualization. Due to the limited availability of observation data, a simpler parameter structure should be considered to produce a more unique solution.

SUMMARY

This report presents the results of a study to describe application of nonlinear least-squares regression to the existing ground-water flow model of the central northern Tampa Bay (CNTB) area. The study has an area of approximately 2,000 mi^2 that includes all of Pasco County, most of Hernando, Pinellas and Hillsborough Counties, and part of Polk County. Six rivers and their tributaries, several small streams along the coast, and some internally drained systems that flow only during extreme rainfall events, define the surface-water system of the study area. The two largest systems are the Hillsborough and Withlacoochee Rivers. There are hundreds of lakes, swampy plains, and intermittent ponds dispersed throughout the study area, ranging in size from less than 1/4 acre to more than 2,500 acres. In the study area, a total of 17 springs are either found inland flowing to adjacent rivers or along the coast discharging directly to the Gulf of Mexico. The ground-water flow system beneath the study area is a multilayered system consisting of a thick sequence of carbonate rock overlain by clastic deposits. The hydrogeologic framework includes the unconfined surficial aquifer system and the confined Upper Floridan aquifer. A low permeablility intermediate confining unit separates the aquifers. The Upper Florida aquifer is underlain by a low-permeablility evaporite limestone that forms the bottom of the fresh ground-water flow system.

Ground-water flow was simulated using MODFLOW, the USGS three-dimensional ground-water flow model. The flow model was linked with a nonlinear weighted least-squares regression routine for solution of the inverse problem. The ground-water flow model constructed for this study was based on existing data and information and assumed steady-state conditions. Regression statistics for the reported parameter values (SDI, 1997), including parameter sensitivities and correlation, were calculated. The analysis procedure consisted of two simulation phases. Phase 1 was designed to calculate parameter sensitivities and correlations for the SDI (1997) parameter values and to assess model parameterization. Phase 2 was designed to determine the optimal parameter values for the hydrologic features of interest using nonlinear regression and to evaluate these optimal values.

A total of 96 parameter-zone values were estimated. Recharge was assumed to be known and specified as an unestimated parameter. Optimal estimates of individual transmissivity-zone values are generally within 50 percent of the initial values and range from a factor of about 13.9 above to a factor of about 0.1 below than the initial values. Optimal estimates of individual leakance-zone values are generally within an order of magnitude of the initial values and range from a factor of about 143.8 above to a factor of about 0.01 below than initial values. The optimal estimate of hydraulic conductivity of the surficial aquifer system is a factor of about 0.78 below than the initial. The optimal estimate of anisotropy of the Upper Floridan aquifer is a factor of about 0.25 below than the initial values. Several estimates of transmissivity of the Upper Floridan aquifer and leakance of the intermediate confining unit are probably outside the range of likely values estimated from field data.

The parameter-estimation model generally produced simulated water levels in close agreement with measured water levels. Approximately 70 percent of the simulated water levels are within 2 ft of the measured water levels and 90 percent are within 5 ft of measured levels. The general directions of ground-water flow and the magnitude of hydraulic gradients simulated in the surficial aquifer system and the Upper Floridan aquifer agree well with the regional ground-water flow system.

It was impossible to independently estimate all parameters given the present zonation structure and observation data sets due to parameter insensitivity and correlation. A simpler parameter structure should be considered. Possible solutions are to (1) collect more water-level data; (2) estimate fewer parameters by either combining zones or assigning values to insensitive parameters; and (3) estimate the most sensitive parameters first, then using the optimized values for the most sensitive parameters as initial values, estimate the entire data set.

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APPENDIX

Appendix. Initial and optimized parameter values, relative composite sensitivity for optimal estimates of input parameter values, and correlation between parameters

[RCS, relative composite sensitivity; ft/d, foot per day; ft/d/ft, foot per day per foot; K, hydraulic conductivity; L, leakance; T, transmissivity; Kx/Ky, horizontal anisotropy ratio]

Parameter-zone number	RCS	Initial value	Optimized value	Correlated parameters	
				Most correlated	2nd most correlated
Hydraulic conductivity of the surficial aquifer system[1] (ft/d)					
K	0.320	[2]1	[2]0.78	L20 (-.56)	L69(-.38)
Transmissivity of the Upper Floridan aquifer[3] (ft^2/d)					
T1	1.000	500,000	610,000	T2 (-.61)	T3 (.52)
T2	0.670	400,000	564,000	L17 (.63)	T2(-.61)
T3	0.110	300,000	441,000	L60 (.84)	L23(-.70)
T4	0.320	250,000	132,500	KxKy(-.43)	T8 (.37)
T5	0.090	130,000	24,700	V65(-.39)	T18,T4 (.15)
T6	0.240	110,000	91,300	T19 (.74)	L25,L47(.36)
T7	0.360	100,000	271,000	L17 (.67)	T (.44)
T8	0.065	70,000	9,100	KxKy(-.78)	K13 (.52)
T9	0.950	60,000	76,200	L66 (.63)	T17 (0.40)
T10	0.720	50,000	58,500	L3 (.31)	KxKy (-.27)
T11	0.130	40,000	34,000	L47(-.84)	L25 (.82)
T12	0.073	35,000	403,200	L17 (.49)	T7 (.39)
T13	0.180	25,000	341,500	KxKy(-.67)	L17 (.53)
T14	0.350	20,000	25,600	L66(-.30)	T12(-.28)
T15	0.016	10,000	700	L26(-.28)	L66 (.19)
T16	0.410	20,000	13,200	KxKy (.42)	L21 (.37)
T17	0.370	20,000	277,200	L54(-.76)	L55(-.51)
T18	0.420	20,000	20,200	T4 (.37)	L49 (.36)
T19	0.280	50,000	31,500	T6 (.74)	L16(-.35)
T20	0.013	300,000	213,000	T23(-.56)	L16(-.31)
T21	0.006	500,000	532,5000	L33 (.18)	L18 (.12)
T22	0.078	130,000	211,900	T23(-.36)	L16 (-.25)
T23	0.210	400,000	1,440,000	L16 (.60)	T20 (-.56)
Anisotropy of the Upper Floridan aquifer[4]					
Kx/Ky	0.310	[2]1	[2]0.25	T8(.78)	T13(-.67)
Leakance of the intermediate confining unit[5] (ft/d/ft)					
L1	0.001	3.50E-01	5.11E-01	L25 (.76)	L47(-.75)
L2	0.200	1.00E-02	1.20E-03	L12(-.18)	L33(-.10)
L3	0.280	6.00E-03	9.60E-04	T10 (.31)	L45 (.13)
L4	0.032	4.00E-03	9.24E-03	L71(-.32)	L68(-.12)
L5	0.130	3.00E-03	3.00E-03	L65(-.39)	T18,T4 (.15)
L6	0.051	2.50E-03	3.15E-03	L23(-.23)	L60 (.13)
L7	0.018	2.00E-03	8.44E-03	L37(-.53)	K13(-.12)
L8	0.026	1.50E-03	7.10E-03	T23(-.24)	T20(-.24)
L9	0.180	1.00E-03	5.30E-04	L61(-.28)	L68(-.21)
L10	0.058	8.00E-04	1.17E-03	L59(-.25)	L11(-.24)
L11	0.026	7.00E-04	1.12E-04	L61(-.31)	L10(-.24)
L12	0.043	6.00E-04	6.83E-03	L21(-.45)	L2(-.18)
L13	0.018	5.00E-04	4.01E-03	L22(-.88)	T18(-.27)
L14	0.310	4.00E-04	1.08E-04	L71 (.17)	L19(-.16)
L15	0.220	3.00E-04	2.85E-04	L26(-.17)	L28(-.15)
L16	0.003	2.00E-04	2.52E-04	T23 (.60)	L22(-.41)
L17	0.014	1.80E-04	7.43E-04	L23(-.79)	T7 (.67)
L18	0.009	1.00E-04	5.90E-05	L21(-.45)	L23(-.23)
L19	0.110	9.00E-05	8.64E-05	L14(-.16)	L66(-.16)
L20	0.300	7.00E-05	1.68E-05	K (-.56)	L20 (.23)

Appendix. Initial and optimized parameter values, relative composite sensitivity for optimal estimates of input parameter values, and correlation between parameters

[RCS, relative composite sensitivity; ft/d, foot per day; ft/d/ft, foot per day per foot; K, hydraulic conductivity; L, leakance; T, transmissivity; Kx/Ky, horizontal anisotropy ratio]

Parameter-zone number	RCS	Initial value	Optimized value	Correlated parameters	
				Most correlated	2nd most correlated
Leakance of the intermediate confining unit[5](ft/d/ft)					
L21	0.001	6.00E-05	2.06E-05	L46 (-.40)	T16(.37)
L22	0.090	5.00E-05	1.03E-05	L13 (-.88)	L33(.31)
L23	0.090	4.00E-05	3.40E-03	L60 (-.83)	L17 (-.79)
L24	0.338	1.00E-05	2.65E-05	L50 (-.30)	L20 (.15)
L25	0.006	1.00E-06	1.99E-06	L47 (-.99)	T11,L70 (.82)
L26	0.027	3.50E-01	1.40E-02	T15 (.28)	L62(-.25)
L27	0.008	1.00E-02	2.86E-02	L33 (.31)	T14(-.17)
L28	0.020	1.00E-02	3.40E-03	L64(-.17)	L15(-.15)
L29	0.002	3.00E-03	4.44E-03	L31 (.33)	L41(-.30)
L30	0.068	3.00E-03	2.55E-03	L11 (.17)	L61 (.12)
L31	0.024	2.00E-03	6.25E-02	L29 (.33)	L35(-.16)
L32	0.048	2.00E-03	1.82E-03	T17(-.13)	L55(-.12)
L33	0.025	1.50E-03	7.50E-04	L27 (.31)	L59(-.22)
L34	0.190	1.50E-03	8.70E-04	L34 (.13)	L71 (.09)
L35	0.069	1.50E-03	3.27E-03	L48(-.28)	L18 (.19)
L36	0.036	1.50E-03	5.10E-04	K8 (.19)	KxKy(-.11)
L37	0.009	1.00E-03	4.04E-03	L7(-.53)	K10 (.05)
L38	0.002	1.00E-03	3.06E-03	L55(-.24)	L11 (.22)
L39	0.096	1.00E-03	1.02E-03	L40(-.80)	L55(-.42)
L40	0.009	1.00E-03	4.00E-05	L39(-.80)	L20 (.23)
L41	0.095	1.00E-03	1.00E-05	--	--[6]
L42	0.023	1.00E-03	1.20E-04	L17(-.46)	L60(-.31)
L43	0.170	1.00E-03	1.60E-03	K17(-.13)	L54 (.09)
L44	0.170	3.00E-04	5.04E-04	L60 (.24)	L46(-.22)
L45	0.029	8.00E-04	3.62E-03	T10 (.13)	L3 (.13)
L46	0.037	8.00E-04	5.52E-04	L60 (-.80)	T3(-.66)
L47	0.001	8.00E-04	5.61E-03	L25 (-.99)	T11,L70(-.84)
L48	0.002	8.00E-04	1.17E-03	L35 (-.28)	T14(-.27)
L49	0.004	8.00E-04	1.21E-03	T18 (.36)	L16(-.29)
L50	0.010	8.00E-04	4.40E-04	L24 (-.30)	T19(.22)
L51	0.250	8.00E-04	6.16E-04	L51(-.34)	L51(-.11)
L52	0.380	8.00E-04	6.24E-04	L52 (.16)	T9 (.13)
L53	0.001	7.00E-04	2.67E-03	L51(-.34)	T9(-.19)
L54	0.008	7.00E-04	1.01E-01	T17(-.76)	L39(-.35)
L55	0.017	6.00E-04	4.26E-02	T17(-.51)	L39(-.42)
L56	0.092	6.00E-04	7.86E-04	T14(-.08)	T8 (.07)
L57	0.120	6.00E-04	4.68E-04	KxKy(.18)	T14(-.15)
L58	0.091	6.00E-04	1.14E-04	T15(-.08)	L26 (.05)
L59	0.004	5.00E-04	6.75E-04	L61(-.81)	L10(-.25)
L60	0.170	4.00E-04	9.20E-05	T3 (.84)	L23(-.83)
L61	0.021	4.00E-04	6.08E-04	L59(-.81)	L9(-.28)
L62	0.190	4.00E-04	3.96E-04	L26(-.25)	K(-.06)
L63	0.610	2.00E-04	2.70E-04	K(-.13)	L20 (.07)
L64	0.039	2.00E-04	4.28E-04	L28(-.17)	T22(-.07)
L65	0.038	2.00E-04	4.22E-04	T6(-.39)	T4 (.13)

Appendix. Initial and optimized parameter values, relative composite sensitivity for optimal estimates of input parameter values, and correlation between parameters

[RCS, relative composite sensitivity; ft/d, foot per day; ft/d/ft, foot per day per foot; K, hydraulic conductivity; L, leakance; T, transmissivity; Kx/Ky, horizontal anisotropy ratio]

Parameter-zone number	RCS	Initial value	Optimized value	Correlated parameters	
				Most correlated	2nd most correlated
Leakance of the intermediate confining unit (ft/d/ft)[5]					
L66	0.006	1.00E-04	3.00E-06	T9 (.63)	T17(.27)
L67	0.120	1.00E-04	1.79E-04	L35(-.14)	T4(.08)L57(-.08)
L68	0.031	4.00E-04	2.72E-04	T17 (.25)	L68,L66(-.21)
L69	0.260	5.00E-05	5.50E-05	K(-.38)	L20(.21)
L70	0.026	4.00E-05	2.00E-05	L47(-.84)	L25(.82)
L71	0.590	3.00E-04	7.11E-04	L4(-.32)	T14(.17)

[1] expected reasonable range of optimized values 1 to 40 feet per day.
[2] value is a multiplier for the spatially variable parameter values.
[3] expected reasonable range of optimized values 10,000 to 1,000,000 feet squared per day.
[4] expected reasonable range of optimized values 0.1 to 20.
[5] expected reasonable range of optimized values 1.0E-06 to 1.0E-02.
[6] not calculated because L41 reached its lower limit of 0.01 times the initial value.