SPECIAL PUBLICATION SJ2006-SP6

A LAKE/GROUNDWATER FLOW MODEL OF THE PIERSON AREA IN VOLUSIA COUNTY, FLORIDA

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October 2002

Final Report

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1.0 INTRODUCTION

This report presents a numerical model of groundwater and lake flow for the Pierson area in northwest Volusia County, Florida (Figure 1). The model simulates changes in water levels and flow rates due to changes in climatic conditions and due to anthropogenic development (well pumping, for example). The report includes a conceptual description of the modeled processes and an analysis of the available hydrologic and hydrogeologic data. The report also describes the methods used to construct the numerical model and the methods used to calibrate the model to observed conditions. The final calibrated model is used to estimate future conditions under different management scenarios.

The overall goal of this project is to better understand the effects of groundwater withdrawal and climatic events on lakes in the Pierson area of northwest Volusia County. The study area includes five "lakes of interest" – Shaw, Pierson, Drudy, Emporia, and Purdom (Figure 2) – on a topographic ridge about five miles east of the south end of Lake George. Several ferneries (fern nurseries) are located in the area. Water withdrawal in the area is primarily for agricultural use. The Pierson area was selected for this study because it is representative of lake systems in the Crescent City and Deland Ridges. This project will serve as a pilot study that may be replicated for other lake groups in the St. Johns River Water Management District (SJRWMD, or "the District").

The District has established minimum flows and levels (MFLs) for each of the five lakes of interest. The MFLs are based primarily on soils and vegetation in and around the lakes. The MFLs for lakes typically include a "frequent high" level, a "minimum average" level, and a "frequent low" level. In some cases an "infrequent high" level and an "infrequent low" level are also established. The established levels define the lake stage frequency/duration characteristics necessary for protection of biotic communities.

The District has modeled four of the five lakes of interest with simple water-budget models. According to these models, two of the lakes of interest – Drudy and Emporia – are meeting MFLs but are currently at capacity (no additional withdrawal possible). Lake Pierson is meeting

MFLs (with excess capacity), and Shaw Lake has been flagged for reevaluation. The District has not modeled Lake Purdom. Each of the lakes has an organic-sediment lakebed, and each one has nearly gone dry during the recent drought. The lakes were probably formed after land subsidence due to dissolution of carbonate rock. Of the modeled lakes, Shaw Lake is believed to be best connected to the water-bearing Floridan Aquifer.

This current project involves development of a MODFLOW (Harbaugh and McDonald 1996) groundwater model of the study area, and includes the five lakes mentioned above in the Lake Package for MODFLOW (Council 1999). The Lake Package simulates groundwater-lake interaction and calculates changes in lake levels. The model was constructed as a zoomed-in cut-out of the Volusia County MODFLOW model already developed by the District (Williams 2002).

In order to establish the ability of the model to accurately simulate groundwater flow and lake level changes, the model is calibrated to observed conditions during the 1995 through 1999 time period. These years include periods of high and low rainfall. Water-level data and lake-stage data are available during this period.

After calibration, the model is used to predict the future changes in groundwater and lake levels under different scenarios. The scenarios incorporate different withdrawal rates for area wells and different direct withdrawal rates from the lakes.

2.0 CONCEPTUAL SITE MODEL

The first step in the modeling process is to define, in general terms, the processes to be modeled and to identify the factors that influence these processes. The end product of this exercise is a conceptual site model, which becomes the framework for the numerical model. The pertinent components of the conceptual site model are discussed below.

2.1 Area of Interest

This study focuses on five lakes – Shaw, Pierson, Drudy, Emporia, and Purdom – covering a 13,000 ft by 17,000 ft area in northwest Volusia County (Figure 2). For the purposes of numerical modeling, the area of interest is expanded to ensure that the distance from the lakes to a lateral model boundary is 2 to 3 times the width of the focus area (Figure 3). This area of interest covers a portion of northwest Volusia County and small portions of southwest Flagler County and eastern Lake County.

2.2 Physical Setting

The lakes of interest are located on a topographic ridge that runs from northwest to southeast (Figure 4). The average stages of the five lakes of interest range from about 35 ft NGVD to 42 ft NGVD. The local topographic high on the ridge is about 100 ft NGVD in the southeast corner of the area of interest. The lowest topographic elevation in the area of interest is along the St. Johns River (southwestern portion of the model domain), which has a stage of about 1.2 ft NGVD at Lake George.

The area of interest includes part of Lake George and portions of the St Johns River upstream (south) of Lake George. Several other streams and lakes are also located within the area of interest. Some of the streams are perennial and others flow intermittently. Numerous wetlands cover portions of the area of interest. These wetlands are typically adjacent to the area streams and lakes. The five lakes of interest all have lakeside wetlands.

2.3 Hydrostratigraphy and Hydrogeologic Properties

The uppermost aquifer in the area of interest is the surficial aquifer system (SAS). This unconfined aquifer is composed of sand, silt, clayey silt, and shell bed deposits from the Pleistocene and Holocene ages (Williams 2002).

An intermediate confining unit (ICU) separates the SAS from the underlying Floridan Aquifer. In the study area, the ICU consists of fine sands and calcareous clays from the Miocene and early Pleistocene ages (Williams 2002).

The Floridan aquifer system is separated into upper and lower aquifer zones by a middle semi-confining unit (MSCU). Limestone and dolomite from the Eocene and Paleocene ages make up much of the permeable Floridan aquifer system. In the MSCU, the deposits are denser and lack the fracture zones and solution cavities in the more transmissive zones (Williams 2002).

The Cedar Keys Formation lies at the base of the Floridan aquifer system, and is composed of relatively impermeable carbonate rocks with abundant evaporite minerals (Williams 2002).

In the study area, the top of the ICU is found at elevations between -70 ft and 10 ft NGVD. The ICU is 4 ft to 40 ft thick. The Upper Floridan aquifer (UFA) is between 100 and 500 ft thick, the MSCU is between 130 and 300 ft thick, and the Lower Floridan aquifer (LFA) is between 1,200 and 1,400 ft thick. The base of the LFA is at elevations of between -2,100 and -1,900 ft NGVD.

Figure 5 shows the conceptual hydrostratigraphic model, including three aquifer layers – SAS, UFA, LFA – and two confining units – ICU, MSCU. For the purposes of modeling, it is assumed that groundwater does not flow across the freshwater/saltwater interface (taken to be the 5000 mg/L chloride surface) nor does it flow across the lower confining unit (Cedar Keys Formation).

Hydrogeologic properties have been estimated for the aquifers and confining units of this conceptual model. Based on aquifer performance tests, the hydraulic conductivity of the SAS is between 4 ft/d and 110 ft/d, and typical values of 20 ft/d to 25 ft/d have been used in groundwater models (Williams 2002). The transmissivity of the UFA in the study area has been measured at values between 9,000 ft^2/d and 50,000 ft^2/d (Williams 2002). Transmissivity estimates for the LFA in east-central Florida range from 200,000 ft^2/d to 670,000 ft^2/d (Williams 2002).

Wide ranges of vertical hydraulic conductivity and leakance (vertical conductivity divided by thickness) have been estimated for the two confining units shown in Figure 5. Based on aquifer performance tests, the leakance of the ICU is between 1 x 10^{-6} d^{-1} and 0.8 d^{-1} (Williams 2002). The vertical conductivity of the MSCU has been estimated to be between 0.005 ft/d and 2 ft/d (Williams 2002).

2.4 Groundwater Sources and Sinks

Groundwater recharge is the primary source of groundwater in the area of interest. Recharge is defined as the rate of water infiltration to the water table. Some of the precipitation falling on the land surface becomes overland runoff, and a significant portion of the water is taken up by roots in the unsaturated zone as evapotranspiration (ET). The remaining water becomes groundwater recharge (Figure 6).

There are many ferneries in the study area. Irrigation is often applied to promote growth in these ferneries. The applied irrigation can add additional groundwater recharge; however, it is typically taken up by the plants as unsaturated-zone ET.

A simple water-balance equation can be used to estimate the volumetric flux of recharge to the saturated groundwater:

$$RECH = P - RO + IRR - ET_{unsat} \qquad (1)$$

In equation 1, recharge (*RECH*), precipitation (*P*), runoff (*RO*), applied irrigation (*IRR*), and unsaturated-zone ET (ET_{unsat}) are all expressed in length/time units (e.g., ft/d). All of the fluxes in equation 1 are variable in space and time.

Pumping wells in the study area act as a significant groundwater sink. Several hundred pumping wells are located within the model boundary. The withdrawn water is typically used for irrigation at ferneries (becoming a groundwater source), with water loss due to ET.

Area lakes, streams, and wetlands can act as both sources and sinks of groundwater. Some water bodies are receptors of discharging groundwater, and others provide groundwater from seepage (Figure 7).

2.5 Groundwater Flow

Saturated-zone groundwater flow is governed by the groundwater flow equation,

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=\frac{S}{b}\frac{\partial h}{\partial t}, \qquad (2)$$

which is a combination of mass conservation and Darcy's Law. In equation 2, the state of groundwater is given by the spatially-variable, temporally-changing potentiometric head field, h. The head depends on specified boundary conditions, initial conditions, the spatial distribution of hydraulic conductivity (K_x, K_y, and K_z), and the spatial distribution of the groundwater storage coefficient (S). For unconfined aquifers, the storage coefficient is equal to the aquifer specific yield, S_y. For confined aquifers, the storage coefficient is the product of specific storage (S_s) and aquifer thickness (b).

In the study area, groundwater generally flows outward from the topographic ridge containing the lakes of interest, with some groundwater moving westward and southward toward the St. Johns river and some moving eastward toward the Atlantic Ocean. There is also a downward component of flow that drives groundwater from the surficial aquifer to the Floridan Aquifer on the topographic ridges. In the lower lying portions of the area of interest the vertical gradient is reversed, indicating discharge from the UFA to the SAS.

2.6 Lakes of Interest

This study focuses on the stage response of five lakes – Shaw Lake, Lake Pierson, Drudy Lake, Lake Emporia, and Lake Purdom. For these lakes, it is necessary to examine all inflows and outflows in order to relate stage changes to environmental conditions. Figure 8 shows the water-budget components of a lake. The rate of change in lake volume (*dV/dt*) can be expressed as a sum of all inflows and outflows:

$$\frac{dV}{dt} = Q_P - Q_E + Q_{RO} + Q_{STRIN} - Q_{STROUT} - Q_{WD} - Q_{GW} \,, \qquad (3)$$

where Q_P is precipitation inflow, Q_E is evaporation, Q_{RO} is runoff to the lake, Q_{STRIN} is flow from streams, Q_{STROUT} is stream outflow, Q_{WD} is direct lake withdrawal, and Q_{GW} is inflow from or outflow to groundwater. Many of these terms may depend on the stage of the lake. For instance, when the lake stage is high, the water surface has a larger area, and the rate of water loss due to evaporation is larger. Also most stream outflows, whether controlled by natural channels or man-made weirs, are dependent on the lake stage. Given lake bathymetry (bottom elevation), the lake stage can be expressed as a function of the lake volume.

2.7 Lake-Groundwater Interaction

The rate of flow between a lake and groundwater is dependent on the hydraulic conductivity and thickness of the lakebed sediments, the stage of the lake, and the hydraulic head in the groundwater beneath the lake. The relationship to describe the net flow from a lake to groundwater can be expressed as

$$Q_{GW} = \int_{A1} \frac{K}{b}(H-h)dA + \int_{A2} \frac{K}{b}(H-BOT)dA + \int_{A3} \frac{K}{b}(TOP-h)dA \,, \qquad (4)$$

where H is lake stage, K is the vertical lakebed conductivity, b is the lakebed thickness, and TOP and BOT are the top and bottom elevations of the of the lakebed sediments. The integrated regions are $A1$, where the lake is "wetted" ($H > TOP$) and the groundwater is connected ($h > BOT$); $A2$, where the lake is wetted and the groundwater is disconnected; and $A3$, where the lake is not wetted (dry) and the groundwater is discharging ($h > TOP$).

In general, a lake can be a seepage lake (flow from lake to groundwater), a discharge lake (flow from groundwater to lake), or a flow-through lake (discharge on one end and seepage on the other). The lakes of interest for this study, which are expressions of the water table in the surficial aquifer, may be any of these types depending on environmental conditions.

2.8 Period of Interest for Calibration

The five-year period from 1995 through 1999 provides a good time to assess the capability of the model to simulate system responses to changing environmental conditions. Several periods of dry and wet weather are included in these years and good data are available for rainfall, well water levels, and lake stages. The model design, as described below, focuses on this period of study.

3.0 DATA SOURCES

SJRWMD has provided data that can be used to design the model and assess model calibration. This section summarizes the available data; the following section, called "Model Construction" explains how this data is used to build the numerical model.

3.1 Geo-spatial Data

ArcView^{TM} shape files have been provided to define the topography and hydrography (water bodies) of the entire study area. These data files have attributes to define water body names and topographic contour elevations within the model area.

For all five lakes of interest plus Cain Lake (between Shaw Lake and Lake Purdom), SJRWMD provided ArcView^{TM} shape files to describe bathymetry. For Drudy Lake and Cain Lake, measured water depths at particular points were provided. For the other four lakes, SJRWMD provided bathymetry elevation contours. Conversion of this information into model-ready input is described in Section 4.10.1.

SJRWMD also provided shape files that describe the spatial distribution of 1) estimated water-table depth and 2) Soil Conservation Service (SCS) runoff curve number. These data are used to calculate net recharge as described in Section 4.7. For these data, SJRWMD used existing geo-spatial data to determine the appropriate values at each model grid (presented in Section 4.2).

The grid-cell-based water-table depth and SCS runoff curve number values were then provided in ArcView™ shape file (polygon) format for use in this model.

Locations of monitor wells, water wells, and surface-water withdrawal points have been provided in ArcView™ shape file format, as have locations of precipitation stations in the area. The surface-water and groundwater withdrawal points have identifiers that indicate which water-use permit they are associated with. A polygon shape file of water-use permit boundaries indicates the land area associated with agricultural permits. These data are used to define irrigation locations and rates for calculation of groundwater recharge, as discussed in Section 4.7.

Geo-spatial representations of area roads, land use, soil type, and surface water basins have also been provided as ArcView™ shape files. Geo-registered images – USGS topography maps and air photos – were also provided.

3.2 Volusia County Model

The MODFLOW data sets for the Volusia County steady-state groundwater flow model (Williams 2002) have also been provided by SJRWMD. These data sets provide the basis for defining model layer elevations, initial hydrogeologic properties, and lateral-edge boundary conditions in the smaller model designed for this study. Along with the data sets, SJRWMD provided a shape file of the model grid with attributes that define model layer elevations and properties.

3.3 Calibration Target Data

Water-level vs. time data have been provided for 42 monitor wells within the area of interest and each of the five lakes of interest. These data, recorded over the 1995 through 1999 time frame, are used to assess model calibration.

3.4 Data to Define Boundary Conditions

SJRWMD has also provided stage measurements for thirteen other lakes (not among the "lakes of interest") within the model area. The stages of these thirteen other lakes are used to define boundary conditions for the groundwater model.

Ponce de Leon Spring is located in the southwest portion of the area of interest. A table of measured water levels and discharge rates for the spring has been provided by SJRWMD along with the location of this spring (shape file format).

SJRWMD has also provided a spreadsheet to define water withdrawals from wells during the 1995 to 1999 time frame. The data are organized by permit. For each agricultural permit, and each month in the period of interest, a total water use is estimated. The estimates are based on 1) the permitted use (e.g., fernery, citrus farm, pasture), 2) the number of acres irrigated (taken from the permit information), and 3) estimated per-acre irrigation rates for each permit type in each month, as estimated by SJRWMD. The town of Pierson has three public-supply wells supplying about 120,000 gal/d on average. SJRWMD has provided monthly withdrawal amounts for the Pierson public-supply wells.

Also provided were daily rainfall data at seven precipitation stations in or near the area of interest, and data on potential evapotranspiration rates in the area. Several reports on evapotranspiration research in central/eastern Florida have also been provided.

4.0 MODEL CONSTRUCTION AND DATA ANALYSIS

The provided data were used to build a numerical model of groundwater flow and lake-groundwater interaction. This section describes the methods that were used to analyze the available data and build model-ready data sets.

4.1 Numerical Simulator

The MODFLOW96 (Harbaugh and McDonald 1996) groundwater flow simulator is used for this modeling analysis. MODFLOW provides a means of solving equation 2 for head (h) with given values for hydraulic conductivity (K_x, K_y, and K_z), specific yield (S_y) and specific storage (S_s). Different types of boundary conditions, including specified head, specified flux, and head-dependent flux, may be specified using MODFLOW's boundary-condition packages (e.g., Recharge Package, Evapotranspiration Package, Well Package, River Package, Drain Package). MODFLOW uses the finite-difference approach to reduce the differential equation (2) to a series of algebraic equations that can be solved with an iterative approximation scheme.

The GeoTrans Lake Package for MODFLOW (Council 1999) has been added to MODFLOW in order to simulate lake stage changes for the five lakes of interest in this study. In transient simulations, the Lake Package computes the lake volume (V) using equation 3 and determines the lake stage that corresponds to the computed volume. The Lake Package also provides a groundwater-flow boundary condition in a manner that is similar to the River Package (see equation 4).

4.2 Model Domain and Grid

A model domain has been selected that covers the entire study area (see Figure 3). The domain has its origin (lower-left corner) at coordinates 445,030 m (easting), 3,221,190 m (northing) in UTM coordinates (Zone 17, 1983 datum). The domain covers 77,500 ft in the x direction and 70,000 ft in the y direction, for a total coverage of 195 square miles.

Horizontally, this domain is discretized into a grid that has 360 rows and 375 columns (Figure 9). The minimum grid-cell size, around the lakes of interest, is 125 ft by 125 ft. The maximum grid-cell spacing is 500 ft.

This model grid overlies perfectly with a portion of the Volusia County model (Williams 2002) grid (rows 18-45, columns 1-31), which has uniform grid spacing of 2500 ft. The new model grid was designed so that each cell fits entirely within one of the Volusia County model cells. This way, transfer of data from the larger scale model to the smaller scale model is straightforward.

4.3 Model Layering

Five model layers are used for this study – one for each aquifer (SAS, UFA, LFA), and one for each confining unit (ICU and MSCU). The tops and bottoms of layers are taken directly from the Volusia County model data sets and supplemental layering data provided by SJRWMD. The location of the freshwater/saltwater interface, taken to be where the concentration of chloride is 5000 mg/L, is assumed to be a no-flow boundary. Therefore, the bottom of a layer is at the base elevation of the corresponding hydrogeologic unit or at the elevation of the saltwater interface, whichever is higher. Where the top of a hydrogeologic unit is below the saltwater interface, the corresponding layer is set to be inactive (outside the model domain).

Figure 10 shows two cross sections through the model domain – one along row 125 and one along column 125. Figure 11 shows the inactive portions of layers 4 and 5, where these layers are completely below the saltwater interface.

4.4 Time Discretization

The numerical model uses "stress periods" of one month for purposes of calibrating to observed conditions between 1995 and 1999. During a MODFLOW stress period, the definitions of groundwater sources and sinks do not change. Thus, quantities such as recharge rate and well withdrawals are specified on a monthly (as opposed to daily or yearly) basis.

The model time step size is one day. Though the definitions of sources and sinks change only monthly, the model time step must be considerably shorter for accuracy. MODFLOW computes the head at each model cell each day during the simulated 1995-1999 time period.

4.5 Hydrogeologic Properties

Hydraulic conductivity and storage properties are defined at each active grid cell in the model. These hydrogeologic properties are key calibration parameters in the model (see Section 5). The aquifer layers (layers 1, 3, and 5) exhibit much higher conductivity than do the aquitard layers (layers 2 and 4). For convenience, it is assumed that all layers are isotropic, meaning that a single conductivity value is used for K_x, K_y, and K_z. While in reality these layers may exhibit anisotropy (K_x and $K_y > K_z$), the structure of the model makes it such that only the horizontal conductivities are important for the aquifer layers (SAS, UFA, LFA) and only the vertical conductivities are important for the confining units (ICU, MSCU). The storage property of interest for the unconfined SAS (layer 1) is the specific yield (S_y). For the other layers, the quantity of interest is specific storage (S_s).

In the field, hydraulic conductivity is often highly heterogeneous – varying greatly from one point to the next within a single aquifer or aquitard unit. In modeling, it is practical to assign a single conductivity value for each hydrogeologic unit – representing the bulk average, or effective, conductivity – or to establish a few zones of hydraulic conductivity in order to match field-observed trends or to achieve a suitable model calibration. The assignment of initial values for hydrogeologic properties is described under "Parameterization and Initial Values" (Section 5.1.2). The description of the final calibrated model (Section 5.2) presents the final hydrogeologic property values used for this model.

4.6 Lateral-Edge Boundaries

Along the lateral edges of the model, boundary conditions are specified in each of the three aquifer units (SAS, UFA, LFA) (Figure 11). The head values are taken directly from the specifications and results of the Volusia County steady-state model (Williams 2002) and are held steady during transient simulations. Note that the lateral boundaries are fairly distant from the area of interest (the lateral boundaries are over five miles from the lakes of interest, whereas the lakes are typically just over one mile apart), which diminishes their effect on results. (The effects of the lateral boundaries on model results are shown to be insignificant in sensitivity analysis, see Section 5.3.)

Along the western model boundary south of Lake George, and along the edges of inactive zones in the LFA (layer 5), MODFLOW's General-Head-Boundary (GHB) Package is used to specify a head-dependent boundary condition. The specifications for these GHB conditions are taken directly from the Volusia County model (Williams 2002), which also used GHB conditions in these areas. On the northern, eastern, and southern edges of the current model, heads are specified in MODFLOW as "constant head" cells (Basic Package). The values assigned at these cells are taken from the simulated 1995 steady-state head field in the Volusia County (Williams 2002) model. Constant-head cells are also used at Spring Garden Lake on the southern boundary, consistent with the Volusia County (Williams 2002) model.

In transient simulations, the lateral-edge boundary conditions in the model remain constant. While this imposition of steady conditions at the model boundaries is not accurate, it is acceptable given that conditions in the focus area of the model are not sensitive to variations of head on the boundary (see Section 5.3).

4.7 Recharge

Groundwater recharge represents the rate of water infiltration that reaches the water table, becoming saturated-zone groundwater. In MODFLOW, recharge rates are specified at each cell and for each stress period in the Recharge Package. In order to quantify recharge, which varies in space and time, it is necessary to consider hydrologic processes occurring at the land surface and in the unsaturated zone. Such processes include precipitation, runoff, irrigation, and shallow (unsaturated-zone) ET (see Figure 6).

For the modeling presented here, analytical calculations are used to model the surface and unsaturated-zone processes for soils. This method makes the numerical lake/groundwater model less complex than it would be if surface-water flow and unsaturated-zone flow were included in the numerical model. The equations used to calculate recharge to the saturated zone are consistent with those used in the steady-state modeling for Volusia County (Williams 2002). The overall recharge equation (1) is simply a water balance that is applied for any area (model cell) and time (simulation period). The components of equation 1 are discussed below. The net recharge is calculated analytically prior to making a MODFLOW simulation.

4.7.1 Precipitation

The Pierson Airport precipitation station, located near the center of the model area (Figure 2), is the source for precipitation data. High-quality, daily precipitation records are available for this station. The precipitation is assumed to be uniform in space over the model domain. Figure 12 shows the variation in precipitation over the period of interest. During the period of interest, there are several periods of relatively high precipitation (e.g., August-September 1995) and periods with very little precipitation (e.g., April-June 1998, October 1998-April 1999).

4.7.2 Runoff

Runoff is calculated on a daily basis for a given land area as a function of the known precipitation rate using the Soil Conservation Service (SCS) Runoff Curve Method (U.S. Department of Agriculture 1986, Grove et al. 1998). For each model cell, an average runoff curve number was calculated (by SJRWMD) from land-use and soil-type characteristics (Figure 13). This runoff curve number (*CN*) varies between 30 for minimum runoff (such as in a sandy, undeveloped karst area) and 95 for maximum runoff (e.g., area with paved surfaces or water bodies). For a precipitation event, the runoff is given by

$$RO = \begin{cases} \dfrac{(P - 0.2S)^2}{P + 0.8S}, \text{if } P > 0.2S \\ 0, \text{if } P \le 0.2S \end{cases} \quad (5)$$

$$\text{where } S = \frac{1000}{CN} - 10$$

This equation is used to calculate daily runoff (in inches) given daily precipitation (in inches). It is assumed that any day's precipitation total occurs in a single precipitation event.

4.7.3 Irrigation

In irrigated areas, such as ferneries, agricultural irrigation (*IRR*) is added to the water balance of equation 1. The rate of irrigation is found by dividing the estimated monthly agricultural water use (expressed in cubic feet per day) by the irrigated area. See section 3.4 for a discussion of the water-use data provided by SJRWMD.

The irrigated areas (particular model cells to receive irrigation) are estimated from available data using an automated procedure. For a given permit, with a specified irrigation area (acres) and with specified groundwater and surface-water well locations, the procedure marks a number of cells near the withdrawal points so that the total irrigation area is approximately correct. Specifically, the procedure is:

1. For each model cell, the following information is known: centroid coordinates, area, SCS runoff curve number, and permit (GRS) number (if the cell centroid is within the defined boundary for a water-use permit).

2. For each permit, the following information is known: permit (GRS) number, location of each associated groundwater and surface-water withdrawal point, irrigation area (taken from permit specifications), and estimated fraction of withdrawal from groundwater (as opposed to surface water, as determined by SJRWMD).

3. Target irrigation areas are established for groundwater withdrawals and surface-water withdrawals for each permit. If the estimated fraction of water use coming from groundwater is 70%, and the irrigated area is 10 acres, then the target groundwater irrigation area is set to 7 acres and the target surface-water irrigation area is set to 3 acres.

4. For each permit, a subset of “eligible cells” is found. Eligible cells are cells that are within the given permit’s boundaries and are on irrigable land. For this analysis, it is assumed that a cell with an SCS runoff curve number less than 86 can be irrigated. A review of air photos and USGS maps indicates that cells with higher curve numbers are typically in wetlands or lakes.

5. Some (or potentially all) of each permit’s eligible cells are flagged for groundwater-derived irrigation (if there is groundwater-derived irrigation) using a procedure that

picks the cells nearest the groundwater withdrawal point(s). Cells are added to the list of irrigated cells until the total area is approximately equal to the target irrigation area for groundwater. The difference between the target irrigation area and the model irrigation area is no more than half the size of a grid cell (the last grid cell flagged or next grid cell to be flagged).

6. Similarly, some (or potentially all) of the remaining eligible cells are flagged for surface-water-derived irrigation.

7. The cells that are flagged for irrigation are assigned an irrigation fraction for groundwater or surface water. This is the fraction of the withdrawn surface- or groundwater that is applied as irrigation at the cell. For example, if four cells of equal size are flagged for groundwater irrigation, then each receives a groundwater irrigation fraction of 0.25. Non-irrigated cells are assigned an irrigation fraction of zero.

In each model stress period (month), at each cell within a permit boundary, the irrigation rate is calculated as the groundwater withdrawal rate (an assumed fraction of total use) times the groundwater irrigation fraction divided by the cell area, plus the surface-water withdrawal rate times the surface-water irrigation fraction divided by the cell area. Figure 14 shows the cells that receive irrigation in the model, and the withdrawal points for irrigation water.

Note that potential irrigation for several permits could not be simulated due to lack of data or inaccurate data. In some cases, no permit boundary was available. In other cases, a permit boundary’s GRS identifier did not match the GRS identifier of any nearby withdrawal points. Where such difficulties arose, irrigation was not simulated.

4.7.4 Unsaturated-Zone Evapotranspiration

Finally, unsaturated-zone ET (ET_{unsat}) is calculated. If there is no applied irrigation, it is assumed that the unsaturated ET rate is equal to the known minimum ET rate (discussed below). Where irrigation is applied, the unsaturated-zone evapotranspiration is set to the sum of the minimum

ET rate and the irrigation rate (i.e. all irrigation is assumed to be taken up by unsaturated-zone ET). Two adjustments to unsaturated-zone ET are then made if necessary: 1) if the unsaturated-zone ET is greater than the known potential evapotranspiration rate (PET, also discussed below), then this PET becomes the unsaturated-zone ET; and 2) if the unsaturated-zone ET is greater than the available water ($P - RO + IRR$), then all of the available water is assumed to be taken up by unsaturated-zone ET, making recharge (*RECH*) zero. The equation to describe ET_{unsat} is:

$$ET_{unsat} = \min(ET_{min} + IRR, \text{PET}, P - RO + IRR) \quad (6)$$

Monthly minimum ET rates are estimated based on a USGS evapotranspiration study for a deforested area in central Florida (Sumner 1996). Figure 29 of that report shows the interpreted cumulative ET amounts for a single year, totaling about 680 mm (27 in). This is taken to be representative of the minimum ET because there was very little vegetation in the area (and little development) during the study period. The curve in the report figure was used to infer monthly ET rates, which are assumed to be applicable as minimum ET for each of the five years in the current model (Figure 15).

Monthly PET (maximum ET, Figure 15) is taken from two sources, as provided by SJRWMD. Prior to May 1998, PET is taken as the average of PET amounts for Daytona Beach and Orlando, as estimated by Smajstrla and others (1984). Starting in May 1998, data from eight nearby Florida Automated Weather Network (FAWN) sites are available for calculating PET. Monthly averages of these eight sites are used in the model from May 1998 through December 1999. The eight FAWN sites are: Apopka, Lake Alfred, Fort Pierce, Ocklawaha, Okahumpka, Pierson, Tavares, and Umatilla. It appears from Figure 15 that using the FAWN sites gives higher PET estimates than using the estimates from Smajstrla and others (1984), although it is possible that PET was greater during the relatively dry years of 1998 and 1999 (less rainfall correlates with greater periods of sunlight and therefore higher PET).

4.7.5 Unsaturated-Zone Delay Time

Due to differences in depth to the water table, it may be expected that a precipitation event in one area (with a shallow water table) would translate into a near-immediate response in the saturated groundwater system, whereas the same event would lead to a delayed response in a different (deeper water table) area. The delay time for the response in a deep water table area may be many days – perhaps up to two weeks. However, implementing a delay time of up to fourteen days for runoff, when other stresses (precipitation, evapotranspiration, etc.) are averaged over monthly periods, does not significantly affect results (see sensitivity analysis in Section 5.3). Therefore, the unsaturated-zone delay time is ignored in this model. It is assumed that the aquifer responds immediately to precipitation events, regardless of depth to water.

4.8 Saturated-Zone Evapotranspiration

The Evapotranspiration Package in MODFLOW is used to compute evapotranspiration from the saturated groundwater zone. The maximum saturated-zone evapotranspiration rate at each cell in each stress period is set to the remaining evapotranspiration potential not used in the calculation of recharge (PET – ET_{unsat}). The evapotranspiration extinction depth (similar to the root-zone depth) is a model calibration parameter (Section 5.1.2) that was initially set to six feet, based on the Volusia County (Williams 2002) model.

4.9 Withdrawal from Wells

As explained in Section 3.4, SJRWMD provided shape files that describe the location of permitted groundwater well withdrawals in the model area. The District also provided spreadsheets that define the estimated monthly withdrawals from groundwater by permit (GRS) number. For permits with multiple groundwater wells, it is assumed that groundwater withdrawal is equally allocated among the groundwater wells. The locations of groundwater withdrawal wells were mapped to model cells (layer, row, column) based on well coordinates and aquifer designations. Most of the wells are in model layer 3 (UFA), and some are in model layer 1 (SAS). The Well Package is used to apply these specified-flux withdrawals in MODFLOW.

Figure 16 shows the estimated agricultural water use for all permits in the model area. The spikes of water use that occur between December and January in each year can be attributed to freeze protection practices.

4.10 Lakes of Interest

In order to simulate lake level responses for the five lakes of interest, the various components of the lake water budget (equation 3) must be accounted for. Also, the geometry of the lake must be specified to relate lake volume to lake stage.

4.10.1 Bathymetry

Lake bathymetry provides the relationship between lake stage and lake volume. For four of the lakes of interest, contours of lake bottom elevation were provided by SJRWMD. Additional topographic contours on the lake shores were used to define bathymetry up to the maximum extent of the lake (at high water). These contours were used to generate lake bottom surfaces, which were interpolated to the model grid using functions in ArcView™ (Figure 17).

Lakeside wetlands at each of the five lakes of interest make it difficult to develop very accurate stage-volume relationship for the lakes, which can lead to some inaccuracy in model results.

4.10.2 Lakebed

The lakes of interest have lakebed sediments that are high in organic content. The flow between lakes and groundwater is determined largely by the lakebed leakance, or conductivity divided by thickness (equation 4). No data are available to describe the vertical conductivity or thickness of the lakebeds. For convenience, a 2 ft thickness is assumed for all of the lakebeds. The vertical conductivity of each lakebed is treated as a calibration parameter (see Section 5.1.2).

4.10.3 Precipitation

Precipitation on each of the five lakes of interest is taken to be the monthly average at the nearby Pierson Airport precipitation station (see Figures 2 and 12). The total precipitation inflow for a given model time step is the precipitation rate times the model-computed lake area at that time step.

4.10.4 Evaporation

No data for lake-surface evaporation in the study area are available. It is assumed in this study that lake evaporation is approximately equal to the estimated potential evapotranspiration (PET) rate (Figure 15). The evaporation outflow for a lake is calculated at each time step as the product of specified evaporation rate and computed lake area.

4.10.5 Runoff and Stream Inflow

Surface water basins have been defined for each of the five lakes of interest (Figure 18). These basins were based on geographic data from SJRWMD that indicated more regional basin boundaries, and on topography contours in the vicinity of the lakes. Surface water runoff to the five lakes of interest is computed for each month by summing the runoff flows at the cells within the lake basins, as computed by the SCS curve number method (see Section 4.7.2).

Stream inflow to the lakes is not modeled explicitly. Rather, it is assumed that the runoff inflow to a lake includes any flow from streams. Also, it is likely that most of the surface-water inflow to the lakes of interest arrives via the lakeside wetlands.

This method of accounting for surface-water inflow to the lakes is a rough approximation of real-world behavior. Many factors can complicate the true rainfall-runoff function including presence of upland lakes (e.g., several other lakes feed into Shaw Lake and may alter the rainfall-runoff response), antecedent moisture conditions (runoff may be over-predicted by the SCS method during dry periods and/or under-predicted during wet periods), and flow in wetlands.

4.10.6 Direct Withdrawal

SJRWMD provided estimates of monthly withdrawal rates from the lakes of interest (Figure 19). Drudy Lake is pumped most heavily according to the estimates. There is no simulated withdrawal from Shaw Lake. While there are permitted withdrawal points on Shaw Lake, it has been District policy since before 1995 to use groundwater wells in place of these surface-water pumps for irrigation water. Like most well withdrawals in the area, the lake withdrawals are for agricultural purposes.

4.10.7 Stream Outflow

Three of the five lakes have stream outlets (Lake Pierson, Drudy Lake, and Shaw Lake). The stage-discharge relationships are all assumed to have the form

$$Q_{STROUT} = CONST\left(H - CUTOFF\right)^{EXPNT} \quad (7)$$

where *CUTOFF* is the minimum stage for stream outflow, and the values of *CONST* and *EXPNT* depend on the characteristics (shape, slope, etc.) of the stream outlet. Each of these three parameters – *CUTOFF*, *CONST*, and *EXPNT* – are treated as calibration parameters (see Section 5.1.2). Surface water modeling done by the District provides some information on possible values for these parameters, but there are no direct field measurements (contemporaneous measurements of lake stage and stream outflow) to define the stream outflow functions.

4.11 Secondary Lakes, Streams, and Springs

Streams and lakes (except for the five lakes of interest) are modeled with the MODFLOW River Package (Figure 20). The lakes that are not part of this study's focus are called "secondary lakes" to distinguish them from the five lakes of interest. These lakes are identified on shape files.

For several of the secondary lakes, SJRWMD provided multiple measurements of stage throughout the calibration period. In the model, the average measured stage is used for these lakes, and the stages are held constant throughout the simulation. (In Section 5.3, a sensitivity analysis is presented that shows that there is little change in results when the stages for these lakes vary monthly.) For lakes that do not have water level measurements, the stages are based on data values in the Volusia County model (Williams 2002) or on stage indications on USGS maps. Similarly, stream stages are held constant during simulation, and were either taken from the Volusia County model (Williams 2002), or interpreted from USGS maps. Stream stage varies along each stream. The conductivities of lakebed and riverbed sediments are treated as calibration parameters in the model (Section 5.1.2).

Ponce de Leon Spring is in the model near the southeast corner of the domain, and is modeled with the Drain Package in MODFLOW. Because this spring is a surface-discharge point for the UFA, the drain cell is placed in model layer 3. The assigned drain conductance for the drain cell is based on an approximate match of stage-discharge data for the spring.

4.12 Wetlands

The MODFLOW Drain Package is also used to represent wetlands in the model area (Figure 21). These drain cells are placed in layer 1 with an elevation equal to topography. The wetland-sediment thickness is arbitrarily assumed to be five feet, and the hydraulic conductivity is treated as a calibration parameter. A wetland drain cell only becomes active when the water table elevation rises above land surface. At that point, the wetland drain removes water from layer 1, representing discharge into the wetland.

In the Volusia County model (Williams 2002), wetlands were not explicitly represented in this manner. However, for early simulations made during calibration of the current model, it was found that including these wetland specifications led to improved model calibration at a few observation wells. But in the final calibrated model (after adjustment of parameter values), the wetlands are an unimportant groundwater sink, as evidenced in a sensitivity simulation presented in Section 5.3.

5.0 MODEL CALIBRATION

In order to assure that this model is a reasonable simulator of environmental processes and response to water use, the model is calibrated to observed conditions during the years 1995 through 1999. After calibration, the model becomes a more reliable tool for estimating the environmental response under future scenarios (Section 6).

5.1 Calibration Procedure

The process of calibration includes: 1) defining the calibration targets (measured values that the model should reproduce), 2) establishing the calibration parameters (the variables that will be adjusted to match the targets), 3) setting goals for the calibration (to establish acceptable conditions for calling the model "calibrated"), and 4) iteratively making simulations and adjusting parameters until the calibration goals have been met.

5.1.1 Calibration Targets

SJRWMD has provided data that define lake stage and groundwater head during the 1995-1999 calibration period. The primary goal of model calibration is to match these observed data as closely as possible.

Originally, 32 observation wells were defined as calibration targets. These wells were all located in the model domain and have multiple measurements of groundwater head between 1995 and 1999. As calibration progressed, it became clear that the important calibration targets were located around the five lakes of interest. Wells that were near model boundaries were therefore excluded from the analysis. Also, a few target wells were excluded because only a few measurements were made there (e.g., well V-0206), because the screen length was too short to give an accurate depiction of the aquifer head (less than 10 ft), or because it was unclear what aquifer zone the well was representative of (e.g., a deep SAS well may be semi-confined and therefore may not be a good target for the single SAS model layer). The final list of twelve observation well targets are listed in Table 1 and plotted in Figure 22. Observed hydrographs for the six SAS observation well targets are shown in Figure 23. Observed hydrographs for the six Floridan Aquifer targets are shown in Figure 24.

Table 1. Observation Wells Used as Calibration Targets

ID	Official Description	Aquifer
V-0525	V-0525 West Pierson UC - SH Water Level	SAS
V-0528	Pierson Airport Surficial Water Level	SAS
V-0202	Franklin Street UC Water Level	SAS
V-0578	V-0578 Shell Harbor Road UC 30 Water Level	SAS
V-0537	Crosby Reality UC Water Level nr Pierson	SAS
V-0535	Kalota UC Water Level nr Pierson	SAS
V-0577	Shell Harbor Road CF Water Level	UFA
V-0066	Pierson Iron CF Water Level	UFA
V-0147	USGS Franklin Street CF Water Level	UFA
V-0531	Pierson Airport Upper Floridan Water Level	UFA
V-0089	Jones nr Pierson CF Water Level	UFA
V-0530	Pierson Airport Lower Floridan Water Level	LFA

Similarly, Figure 25 shows the observed hydrographs for the five lakes of interest. These hydrographs are also used as calibration targets for the lake/groundwater model. Data for Lake Pierson after September 1996 are unavailable.

In many groundwater flow models, stream baseflow data are used to supplement head targets during calibration. In the current model's study area, however, there are no useful baseflow measurements for calibration.

5.1.2 Parameterization and Initial Values

Section 4 presents the details of the model construction, and indicates which specifications are left as variables, or adjustable calibration parameters, in construction of the model. In this model, the following specifications are treated as calibration parameters:

- hydraulic conductivity of aquifers and aquitards
- specific yield of the SAS (layer 1),
- specific storage of the ICU, UFA, MSCU, and LFA (layers 2-5),
- lakebed conductivity for each of the five lakes of interest,

- lake outlet parameters (*CUTOFF*, *CONST*, and *EXPNT*),
- evapotranspiration extinction depth, and
- lakebed, streambed, and wetland-bed sediments for other boundary conditions.

Initial values of aquifer and aquitard hydraulic conductivities are taken from the specifications in the Volusia County (Williams 2002) model. In the SAS (layer 1), the conductivity is initially set to a uniform value of 20 ft/d. The ICU (layer 2) is not represented as a separate layer in the Volusia County (Williams 2002) model, but is represented in the vertical leakance between the SAS and the UFA. The implied vertical conductivity of the ICU in the Volusia County (Williams 2002) model was determined multiplying that leakance (at each row and column) by the thickness of the ICU. The resulting conductivities were approximately 0.002 ft/d in the area of interest for this study, and did not vary greatly. Therefore, the initial conductivity of model layer 2 was set to a uniform value of 0.002 ft/d.

In the Volusia County (Williams 2002) model, there are several zones of conductivity in the UFA. The current model adopts those zones and zone locations (Figure 26), and uses that model's calibrated conductivity values as initial estimates. The values range from 25 ft/d to 800 ft/d. The MCSU has an approximate vertical conductivity of 0.008 ft/d in the Volusia County (Williams 2002) model, as interpreted by multiplying leakance by thickness. The LFA conductivity is 30 ft/d in the Volusia County (Williams 2002) model.

The specific yield of the SAS is initially set at 0.3. This is a typical value for specific yield. For specific storage, values between 2×10^{-8} ft^{-1} and 10^{-6} ft^{-1} are used, based on estimates of storage coefficients from aquifer pump tests in the region.

Several parameters are used to define lake-to-groundwater and lake-to-stream connections for the five lakes of interest. The lakebed conductivities are initially set at 0.1 ft/d. For the stream outflow equations (see equation 7), initial values are set to create stage-discharge functions that are similar to the functions used in prior lake budget modeling done by the District (Figure 27).

The evapotranspiration extinction depth is initialized at 6 ft to be consistent with the Volusia County (Williams 2002) model. Likewise, lakebed (secondary lakes) and streambed conductivity values are taken from that model. The wetland conductivity is initialized at 0.1 ft/d (like the lakes of interest) to represent a sediment bed that is somewhat less permeable than the underlying aquifer due to organic deposition in soils.

Table 2 lists the model parameters, their initial values, and their assumed reasonable ranges. The hydraulic conductivity ranges are based on aquifer pump test data (see Section 2.3), and the other parameter value ranges are based on typical values and prior modeling experience.

5.1.3 Calibration Goals

For this study, calibration quality is assessed primarily by visual comparison of modeled heads and stages to the measured values shown in Figures 23 through 25. This type of comparison is subjective by nature and requires good judgment on the part of the modeler. Because the calibration assessment is qualitative, the overall goal is also qualitative. In this case the overall goal is to match the observed hydrographs (Figures 23 through 25) as closely as possible.

Objective statistics (average error, root-mean-square error, and mean absolute error) are also calculated for certain simulations, especially when using automatic parameter estimation (see Section 5.1.4 below). When objective statistics are used, a few points on each observed hydrograph are used as target values. The model error, as measured by objective statistics, should ideally be minimized by the calibration process.

5.1.4 Calibration Simulations and Parameter Adjustment

Calibration of the model is achieved by making simulations with the model, plotting the results along with the observed data, adjusting parameter values within their reasonable ranges, and re-simulating until the best possible match is achieved. During the calibration, each parameter is varied in order to get an indication of parameter sensitivity. Those parameters that do not affect calibration quality can be held at their initial values, and more attention can be focused on the parameters that influence the match to observed conditions.

Table 2. Initial Values for Model Parameters

Parameter		Initial Value	Reasonable Range		
Hydraulic Conductivity (K) (ft/d)	SAS	20	4	to	110
	ICU	0.002	10^{-5}	to	10
	UFA	(Figure 26)	20	to	500
	MSCU	0.008	0.005	to	2
	LFA	30	15	to	500
Specific Yield	SAS	0.3	0.1	to	0.4
Specific Storage (ft^{-1})	ICU	10^{-7}	10^{-8}	to	10^{-5}
	UFA	10^{-6}	10^{-8}	to	10^{-5}
	MSCU	2×10^{-8}	10^{-8}	to	10^{-5}
	LFA	2×10^{-6}	10^{-8}	to	10^{-5}
Lakebed K (ft/d)	Lake Pierson	0.1	10^{-4}	to	10
	Drudy Lake	0.1	10^{-4}	to	10
	Lake Emporia	0.1	10^{-4}	to	10
	Lake Purdom	0.1	10^{-4}	to	10
	Shaw Lake	0.1	10^{-4}	to	10
Stage-Discharge *CUTOFF* (ft)	Lake Pierson	33.5	32.5	to	34.5
	Drudy Lake	41.9	40.9	to	42.9
	Shaw Lake	38.0	37.0	to	39.0
Stage-Discharge *CONST*	Lake Pierson	1.092×10^{5}	0	to	10^{6}
	Drudy Lake	6.130×10^{5}	0	to	10^{6}
	Shaw Lake	4.334×10^{5}	0	to	10^{6}
Stage-Discharge *EXPNT*	Lake Pierson	2.658	1	to	4
	Drudy Lake	3.372	1	to	4
	Shaw Lake	3.303	1	to	4
ET Extinction Depth (ft)		6	4	to	20
Lakebed K (ft/d)	Secondary Lakes	From Regional Model	10^{-4}	to	10
Streambed K (ft/d)	All Streams	From Regional Model	10^{-4}	to	10
Wetland Bed K (ft/d)	All Wetlands	0.1	10^{-4}	to	10

For this study, two simulations are made when testing a parameter value set. First, a steady-state simulation is made using average monthly recharge and water use, and with lake stages held at their average levels (averages taken over the 1995-1999 time frame). The computed steady-state heads are then used as initial conditions for the transient 1995-1999 simulation. Heads at observation wells and stages at lakes of interest are saved for each simulated day (heads are bi-linearly interpolated to well locations using a customized “Hydrograph Package” for MODFLOW) so that they can be plotted on the same graphs as shown in Figures 23 through 25.

During the calibration process, it was found that the most sensitive parameters were the conductivities of the SAS, ICU, and UFA (layers 1-3), and the ET extinction depth. The lake levels were also affected by changes in the stage-discharge equations. Conversely, it was determined that changing conductivities in the MSCU and LFA had little effect on results. Changes in lake, stream, and wetland conductivities also had little effect (even for the five lakes of interest). The reasons for limited sensitivity to lakebed conductivity for the five lakes of interest is that the water budgets for these lakes are controlled largely by surface-water processes (runoff, direct precipitation, stream outflow, and evaporation) and the vertical resistance between the lakes and the main (Floridan) aquifer is in the ICU, not the lakebed.

Recognizing that Shaw Lake, and perhaps Lake Emporia, are sink-hole lakes that are now well-connected to the UFA (dissolution in the UFA may have caused the ICU to break apart locally as the sink-holes were formed), zones of higher conductivity were introduced in the ICU (layer 2) beneath these two lakes. These zones helped calibration, as did a similar zone at what appears to be a pair of small sink-hole lakes west of Shaw Lake (near target well V-0537). Figure 28 shows the zones that were introduced in the ICU during calibration.

Also, a stream discharge function was added for Lake Purdom to represent the diffuse outflow from that lake toward the north (toward Cain Lake). This change improved calibration for that lake and appeared reasonable from a review of the applicable USGS quadrangle map. SJRWMD has not constructed a water-budget model for Lake Purdom.

After proceeding with the calibration manually for many simulations, an automatic parameter estimation procedure was used to try and improve the calibration quality. Using a program called PEST (Watermark Numerical Computing 2000) as part of the MODFLOW pre-processor, sensitive parameter values (hydraulic conductivities in layers 1-3 and ET extinction depth) were modified using a nonlinear optimization algorithm until the root-mean-square error was minimized. The final calibration simulation was made manually using parameters that were similar to those determined through the automatic calibration process.

5.2 Calibration Results

Many of the parameter values listed in Table 2 were changed during the course of calibration in order to improve calibration quality. It was found that lower conductivity values in the UFA led to better calibration, when coupled with the right combination of other parameter values. In the end, the conductivity value for the SAS was also lowered from 20 ft/d to 4 ft/d, and the default conductivity of the ICU was raised from 0.002 ft/d to 0.003 ft/d. The ICU sink-hole zones were set to values between that of the SAS and the default ICU, with the sink-hole at Shaw Lake having the highest conductivity in the ICU (0.5 ft/d). Other parameters were either not adjusted due to insensitivity, or left at their initial values because they proved to be reasonable during calibration (changes in other parameters were enough to bring the model into calibration). The final parameter values for the calibrated model are listed in Table 3.

Figure 29 shows the calibration match to the SAS water-level hydrographs. Here the match is good for wells V-0202, V-0578, and V-0535. The match at V-0525 is good except for the final year. This well is adjacent to a large wetland, which is modeled with drain cells. However, the drain cells in this location are not removing water from the model. The relatively flat observed hydrograph at V-0525, and the underestimated head at V-0577 (further discussed in the next paragraph) suggests the possibility that the wetland is acting like a strong head-controlling boundary, and may truly be receiving more water from the UFA in this area. The very flat observed hydrograph at V-0528 was not matched well in any simulation made with the model. There is no evidence of a controlling constant-head type boundary near this well (on the Pierson Airport property). It could be that some local phenomenon is leading to the flat hydrograph at this well, or that a more extensive system complexity affects the hydrograph for this well more than others. The last SAS target well, V-0537, is interesting because the match starts off poor in the first two years, and becomes reasonable by 1997. Before a sink-hole zone was added to the model near the location of this well, the model consistently over-predicted the head there. The observed head fluctuations and overall head drop may have been influenced by sink-hole activity occurring during the five-year calibration period.

Table 3. Calibrated Values for Model Parameters

Parameter		Initial Value	Reasonable Range			Calibrated Value
Hydraulic Conductivity (K) (ft/d)	SAS	20	4	to	110	4
	ICU	0.002	10^{-5}	to	10	(Figure 28)
	UFA	(Figure 26)	20	to	500	Reduced 20%
	MSCU	0.008	0.005	to	2	0.008
	LFA	30	15	to	500	30
Specific Yield	SAS	0.3	0.1	to	0.4	0.3
Specific Storage (ft^{-1})	ICU	10^{-7}	10^{-8}	to	10^{-5}	10^{-7}
	UFA	10^{-6}	10^{-8}	to	10^{-5}	10^{-6}
	MSCU	2×10^{-8}	10^{-8}	to	10^{-5}	2×10^{-8}
	LFA	2×10^{-6}	10^{-8}	to	10^{-5}	2×10^{-6}
Lakebed K (ft/d)	Lake Pierson	0.1	10^{-4}	to	10	0.1
	Drudy Lake	0.1	10^{-4}	to	10	0.1
	Lake Emporia	0.1	10^{-4}	to	10	0.1
	Lake Purdom	0.1	10^{-4}	to	10	0.1
	Shaw Lake	0.1	10^{-4}	to	10	0.1
Stage-Discharge *CUTOFF* (ft)	Lake Pierson	33.5	32.5	to	34.5	33.5
	Drudy Lake	41.9	40.9	to	42.9	41.9
	Lake Purdom	N/A	35.0	to	37.0	36.0
	Shaw Lake	38.0	37.0	to	39.0	38.0
Stage-Discharge *CONST*	Lake Pierson	1.092×10^{5}	0	to	10^{6}	1.092×10^{5}
	Drudy Lake	6.130×10^{5}	0	to	10^{6}	6.130×10^{5}
	Lake Purdom	0	0	to	10^{6}	3.900×10^{5}
	Shaw Lake	4.334×10^{5}	0	to	10^{6}	4.334×10^{5}
Stage-Discharge *EXPNT*	Lake Pierson	2.658	1	to	4	2.658
	Drudy Lake	3.372	1	to	4	3.372
	Lake Purdom	N/A	1	to	4	3.100
	Shaw Lake	3.303	1	to	4	3.303
ET Extinction Depth (ft)		6	4	to	20	6
Lakebed K (ft/d)	Secondary Lakes	Regional Model	10^{-4}	to	10	No Change
Streambed K (ft/d)	All Streams	Regional Model	10^{-4}	to	10	No Change
Wetland Bed K (ft/d)	All Wetlands	0.1	10^{-4}	to	10	0.1

Figure 30 shows the calibration match to the Floridan Aquifer wells. Overall this is a good match, with the exception of V-0577. At this location the model results show very little head difference between the UFA (V-0577) and the SAS (V-0525, Figure 29), whereas the observed data indicate that the UFA head is about five feet higher than the SAS head. This may be evidence of a lower-conductivity ICU in that area, or evidence that the wetland near V-0525 is a strong groundwater sink (water may be moving upward from UFA to SAS in the vicinity of the wetland edge rather than moving horizontally in the UFA toward Lake George). Conversely, the modeled head difference between the LFA and UFA at V-0530 and V-0531 is much larger than the observed difference. This appears to be due mostly to head-dependent (GHB) boundary conditions on lateral edges that are taken from the Volusia County model (especially for the LFA well V-0530). The observed water-level dips in the Floridan Aquifer wells around January of each year are simulated in the model, though the large observed dips (over 20 feet) at V-0147 and V-0089 are not fully replicated. The observed hydrographs indicate many short-term fluctuations that are not simulated in the model, probably because using a stress period length of one month cannot capture pumping changes that occur more frequently.

Finally, Figure 31 shows the calibration to the lake-level hydrographs. The match is very good at Lake Purdom and Lake Pierson (where data are available), and is fair at Shaw Lake, Lake Emporia, and Drudy Lake. It proved to be difficult to match all portions of the hydrographs for these lakes with any set of parameter values. Perhaps this is due to complexities in the flow systems that are not being modeled as part of this study (e.g., upland lake storage, land development in the watershed, sinkhole development during the calibration period, complex surface-water or unsaturated-zone flow). Still, the overall trends and approximate stage magnitudes are captured fairly well for all five lakes.

The average (steady-state) areal distribution of simulated head is shown in Figures 32 (SAS) and 33 (UFA). The SAS exhibits much greater head variability than the UFA, indicating that SAS heads are locally influenced by various factors including presence of water bodies, topography, and runoff/ET variation. Table 4 lists the simulated model-wide groundwater budget for the steady-state (average 1995-1999) calibrated model. Note that the GHB inflow and river outflow are large, due in part to flow that enters the model from the GHB on the western side of the model and discharges directly into Lake George. If these boundary-to-boundary flows are removed, the dominant inflow is from recharge and the dominant outflow is to evapotranspiration. Figure 34 shows the changes in some of the groundwater flow components during the 5-year transient calibration simulation.

Table 4. Groundwater Budget for the Calibrated Steady-State Model

Component	Inflow (ft^3/d)	Outflow (ft^3/d)
Recharge	1.97×10^7	0
Saturated-Zone ET	0	1.64×10^7
Wells	0	1.15×10^6
Lakes of Interest	2.19×10^5	9.01×10^4
Secondary Lakes and Streams	1.30×10^5	5.34×10^7
Wetlands and Spring	0	2.20×10^6
General-Head Boundaries	4.62×10^7	2.24×10^5
Constant-Head Boundaries	8.01×10^6	9.04×10^5
Total	7.44×10^7	7.44×10^7

The average volumetric budget for each lake is shown in Table 5 (averaged over the transient calibration simulation). Figure 35 shows the water budget components throughout the simulation. At Lake Pierson, the primary inflow is from runoff, and the primary outflow is stream outflow. Several budget components – net precipitation, runoff/withdrawal, and groundwater seepage – have about equal influence on Drudy Lake and Lake Purdom, and there are occasional spikes in stream outflow for these lakes. At Lake Emporia, the primary budget components are net precipitation and groundwater seepage. Shaw Lake has a high runoff inflow that is balanced primarily by a high seepage outflow that can be attributed to this lake's good connection with the UFA.

Table 5. Average Lake Budget for the Calibrated Model

Flow Component (positive – flow into lake, negative – flow out of lake)	**Lake Pierson**	**Drudy Lake**	**Lake Emporia**	**Lake Purdom**	**Shaw Lake**
Precipitation – Evaporation (cfs)	-0.059	-0.056	-0.067	-0.067	-0.129
Runoff – Withdrawal (cfs)	0.566	-0.088	-0.037	-0.018	0.955
Stream Outflow (cfs)	-0.808	-0.012	0	-0.117	-0.0001
Net Seepage (cfs)	0.279	0.092	0.034	0.168	-1.034
Total (cfs) (negative because stage decreases)	-0.022	-0.064	-0.069	-0.034	-0.208

5.3 Calibration Sensitivity Analysis

During the calibration sensitivity analysis, each parameter value is systematically raised and lowered from its calibrated value in order to see the effect on results. Parameter value adjustments are made within their established reasonable ranges (see Tables 2 and 3). For sensitive parameters, a small change in parameter value leads to a much poorer match to observed conditions – these parameter values are well defined by the calibration. For insensitive parameters, changes up to their limits of reason do not significantly affect the calibration quality – these parameters remain uncertain estimates.

Figure 36 shows the sensitivity of simulated head in the SAS to changes in the SAS hydraulic conductivity. (Note that when the two lines in these plots are nearly identical, e.g., well V-0578, then the two lines appear as a single line.) In this simulation, the SAS conductivity was raised by 50% from the base value (i.e. raised from 4 ft/d to 6 ft/d). The simulated heads at target SAS wells go down as a result by a small, but noticeable, amount – about 0.9 ft on average. Changes in head in the UFA and changes in lake levels are less pronounced. Table 6 shows the average effect on simulated heads and lake levels for this sensitivity simulation and several others that are discussed below. The averages listed in this table are computed by first taking the average difference between modeled base-case head and sensitivity-simulation head at each well and lake. Then, averages of these values are taken for presentation in the table – one average value for the six SAS wells, one value for the six Floridan Aquifer wells, and one value for the five lakes of interest.

Reducing the default-zone ICU conductivity by 50% has a pronounced effect on simulated heads in all aquifers and on the lake levels of Shaw Lake, Drudy Lake, and Lake Emporia (Figures 37, 38, 39, Table 6). The effect of lowering the ICU conductivity is generally to raise heads in the SAS (above the ICU) and lower heads in the Floridan Aquifer (below the ICU). Because the UFA heads are decreased, and because Shaw Lake is well connected to the UFA, the level of Shaw Lake is dramatically decreased also. As a result of SAS water-level increases, the stages of Drudy Lake and Lake Emporia rise slightly in the sensitivity simulation. The simulated levels of

Shaw Lake and Lake Emporia are strongly affected when a change is made to the hydraulic conductivity of the sink-hole zones in the ICU below these two lakes (Figure 40).

Table 6. Summary of Sensitivity Simulations

Model Adjustment	Average Effect on Calibration Targets		
	SAS Water Level (ft)	UFA Water Level (ft)	Lake Stage (ft)
SAS Conductivity x 1.5	-0.90	-0.24	0.15
ICU Default Conductivity x 0.5	1.57	-4.25	-0.55
ICU Sink-Hole Conductivity x 0.5	0.43	-0.06	0.38
UFA Conductivity x 1.5	-0.71	-2.02	-0.82
MCSU Conductivity x 0.5	0.01	0.04	0.03
LFA Conductivity x 1.5	0.00	-0.01	0.00
ET Extinction Depth x 2	-2.91	-1.75	-1.05
PET from Smajstrla et al.	0.27	0.23	0.31
Specific Yield x 1.5	-0.05	-0.01	0.07
Specific Storage x 2	0.00	0.00	0.00
Stream Outfall Elevations + 1 ft	0.00	0.01	0.36
Stream *CONST* x 0.5	0.00	0.00	0.07
Lake Package K x 0.1	-0.06	-0.09	0.04
River Package K x 0.1	0.10	0.33	0.15
Variable Stages for Secondary Lakes	0.00	0.00	0.00
Removal of Wetland Drains	0.03	0.09	0.04
Constant Heads x 1.15	0.06	0.32	0.07
General-Head Boundaries x 1.15	0.04	0.34	0.04
Unsaturated-Zone Delay Time	0.25	0.07	0.05

The UFA represents the important transmissive zone for this model because it is thick, it has high hydraulic conductivity, and it is not isolated from water bodies and aquifer pumping the way the LFA is. Raising the conductivity of this aquifer by 50% lowers heads throughout the model (Figures 41, 42, 43, Table 6), but especially in the UFA. Shaw Lake and Lake Emporia are affected more than other lakes when the UFA heads are affected because of their relatively close connection with this aquifer.

Sensitivity runs with changes to the MSCU and LFA hydraulic conductivities indicate that the calibration is insensitive to these parameters (Table 6).

When the ET extinction depth is increased from six feet to twelve feet, saturated-zone ET can occur in a larger portion of the model domain. The effect on heads is significant (Figures 44, 45, 46, Table 6), especially in the SAS. The effect on Lake Pierson and Lake Purdom is much less pronounced than the effect on Shaw Lake, Drudy Lake and Lake Emporia because the former lakes have significant stream outflows (Figure 35) that keep stages relatively stable when seepage increases or decreases. Figures 47, 48, and 49 show what happens if the PET values calculated by Smajstrla and others (1984) are used in May 1998 through December 1999, rather than switching to the higher PET values obtained from FAWN data (see Section 4.7.4). There is a small but noticeable increase in SAS, Floridan, and lake water levels in the last year and a half of the simulation due to the decreased ET.

Increasing the specific yield of the SAS by 50% leads to a model with more subdued head variations in that aquifer (Figure 50). There is very little effect on the Floridan Aquifer heads or lake levels. Changes in the specific storage values of all model layers by a factor of two had essentially no effect on model results (Table 6).

Figure 51 illustrates the effect of adjusting the lake outfall elevation – one factor controlling the stream-discharge functions. In the sensitivity simulation, stream outlet elevations (*CUTOFF* variable) were raised by one foot for Lake Pierson, Drudy Lake, Lake Purdom, and Shaw Lake (Lake Emporia does not have a stream outlet). The results indicate that such changes can have significant effects on the lakes where they are applied, and that there is no effect on aquifer heads due to such changes (Table 6). There is little effect on Shaw Lake because the simulated stage is rarely above the outlet elevation in either the base case (calibration) or sensitivity simulation. The effect of reducing the outflow rate (*CONST* variable) by a factor of two, instead of raising the outlet elevation, is small (Table 6).

The model is not sensitive to changes in the lakebed conductivity for any of the lakes of interest. When the lakebed conductivities are reduced by a factor of ten, the simulated hydrographs are virtually indistinguishable from the base-case results (indicated by small values in Table 6). Changing the conductivity of all river cells (includes streams and secondary lakes) by an order of magnitude also has very little effect. When the stages at secondary lakes are varied monthly (where data are available) rather than held constant at their average values, there is no impact on the head at calibration wells or lakes of interest (Table 6, see also Section 4.11). This result justifies the simplification of setting those stages to constant values.

The wetland drains were originally included in the model because they had a significant effect on head at some of the SAS wells. However, after making adjustments for calibration, the wetland drains receive little flow. When the wetlands are removed from the calibrated model (Table 6), the calibration is not substantially changed.

In addition to testing parameter values, two sets of sensitivity simulations test the importance of setting accurate heads at the model's specified-head boundaries. In one simulation the head at all constant-head (Basic Package) cells is raised by a factor of 1.15 (raising the highest constant head of 78.1 ft, NGVD, in the southeastern corner by almost 12 ft, and raising the average specified-head value of 22 ft, NGVD, by over 3 ft). This change has a negligible effect on results except at well V-0530 (the lone LFA target), where heads rise about 0.7 ft. Similarly, increasing the general-head boundary (GHB) heads by a factor of 1.15 (raising the maximum head of 50.4 ft, NGVD, by over 7 ft, and the average head of 22 ft, NGVD, by over 3 ft) only affects well V-0530 (the increase is about 1.2 ft for this well, Figure 52). The LFA well is most affected by the lateral boundary changes because this well is isolated from other controlling boundary conditions by the MSCU.

A final sensitivity simulation was made to test whether implementation of an unsaturated zone delay time for net recharge would affect results (see Section 4.7.5). Where the water table is shallow (approximately less than two feet), no delay time is assumed. Where the water table is deep (six feet or greater), a two-week (fourteen day) delay time is assumed. For intermediate depths (at least two feet but less than six feet), a one-week (seven day) delay time is assumed. For simplicity, the delay time (*DELAY*) is only applied to precipitation (*P*) and runoff (*RO*) in equation 1. If a given model period begins on day *X*, and ends on day *Y*, then the total precipitation for that period is calculated by adding the precipitation for days (*X* – *DELAY*) through (*Y* – *DELAY*). A time period's total runoff is similarly computed (note that this method also delays runoff into the lakes, though this is unrealistic). Figure 53 and Table 6 show that this change has a small effect on SAS heads, and even less effect on the Floridan Aquifer heads and lake levels.

5.4 Calibration Assessment

While the calibration to observed hydrographs is not ideal (Figures 29-31), the model does reproduce the approximate magnitude of most of the observations and generally captures the trends in the observed data. Furthermore, many variations in parameter values were attempted and did not lead to better calibration quality. Based on these facts, the current model is taken to be the "calibrated lake/groundwater model" for use in predictive analysis (next section).

It is recognized, however, that other sets of parameter values could also result in a reasonable model calibration. Also, the calibration is quite insensitive to some parameter values, meaning that their values are not determined at all by the calibration analysis. These facts should be kept in mind when drawing conclusions from the predictive analysis.

Many real-world factors can lead to the head variations observed at target wells and lakes of interest. The model presented here incorporates the general effect of many environmental factors – precipitation, evapotranspiration, well withdrawal, etc. – in a simplified manner that is consistent with the accuracy of available data and the overall goals of the project. The model does not and cannot account for many real-world complexities of lake and groundwater flow due to lack of available data, incomplete understanding of the physical processes, and/or inherent limitations of the analytical and numerical approaches.

If the model limitations and assumptions are kept in mind, then the model can be a useful tool for evaluating the future response of the lake and groundwater flow systems to postulated conditions. While the exact magnitude of predicted heads, lake stages, and flow rates will not always be accurate, the relative effect of one scenario vs. another should be valid. This information should be useful to water planners when devising management policies for the area.

6.0 PREDICTIVE ANALYSIS

The calibrated model of lake/groundwater interaction and groundwater flow is used to predict future conditions under several potential scenarios. The scenarios include climatic extremes (wet and dry periods) as well as changes in water use. In general, water use increases may result from additional crop planting in the area. Conversely, water use may decrease due to more efficient irrigation methods, conservation practices, or regulatory action to reduce consumptive use permits.

6.1 Predictive Analysis Model Construction

In order to compare the results of future scenarios, 30-year transient simulations are made with the calibrated model. This long time period is used so that meaningful and accurate lake stage statistics can be synthesized. These statistics, in the form of stage-duration relationships, are sometimes compared to minimum levels to assess whether a lake is likely to meet its MFLs (discussed further in Section 6.2).

Actual rainfall data are used for the 30-year predictive simulations. These data are taken from daily precipitation records at the Pierson Airport for the period 1970 through 1999 (Figure 54). Note that the last five years of this 30-year period coincide with the model calibration period (Section 5). The period includes extremely wet years (e.g., 1992 with 64.9 in) and extremely dry years (e.g., 1999 with 37.5 in). The SCS curve number method is used to compute daily runoff at each model grid cell, and then total monthly runoff values are calculated for each cell in each of the 360 months of the simulation (see Section 4.7.2 for additional details on the method).

For the other time-varying inputs in the model – water use, PET, and minimum ET – average monthly values are used. These values are based on the 1995 through 1999 data. For each water-use permit, the 1995 through 1999 estimates are used to determine the average monthly water use in all 12 months of the year. Thus, a unique water-use value is used for each month and each permit, but the same value is used for a given month in each simulated year. Total agricultural water use is graphed in Figure 55. For PET (and lake evaporation), the average monthly values of Smajstrla and others (1984) are used, as they are in the first part of the calibration simulation.

The monthly minimum ET rates used in the calibration simulation are also used in the predictive simulations. Net recharge to the groundwater is computed using the methods described in Section 4.7.

Other model inputs (e.g., river stages, boundary heads, secondary lake levels) are held constant throughout the 30-year simulation. The sensitivity analyses of Section 5 justify these simplifications. Future changes in land use that may affect results are largely unknown and are therefore ignored.

6.2 Measurement of Performance

The District has established minimum levels for each of the five lakes of interest based primarily on soil and vegetation types (Neubauer 1993, 1994, Richardson 2000, Ware 2001, Hall and Robison 2001). These levels are now part of the Florida Administrative Code (Chapter 40C-8). Table 7 lists these minimum levels for the lakes of interest. The levels define, in general terms, the frequency and duration of conditions required to protect aquatic habitats and wetlands.

Table 7. Minimum Levels for Lakes of Interest

MFL Category	Lake Pierson (ft NGVD)	Drudy Lake (ft NGVD)	Lake Emporia (ft NGVD)	Lake Purdom (ft NGVD)	Shaw Lake (ft NGVD)	Approximate Percent of Time Above Level
Minimum Infrequent High	not defined	not defined	not defined	not defined	38.5	5%
Minimum Frequent High	34.4	42.1	38.9	37.0	36.9	20%
Minimum Average Level	33.8	40.6	35.8	36.4	36.2	50%
Minimum Frequent Low	32.4	39.1	34.3	35.0	34.0	80%
Minimum Infrequent Low	not defined	not defined	not defined	not defined	32.0	95%

For all of the lakes, three different minimum levels have been established: the "minimum frequent high" level, the "minimum average" level, and the "minimum frequent low" level. The minimum frequent high level represents an elevation that should be "seasonally flooded" by the lake (30 days or more during each growing season). The minimum frequent high should be exceeded approximately 20% of the time or more (see Figure 1 in Richardson 2000, Ware 2001, or Hall and Robison 2001). The minimum average level is an elevation that should be "typically saturated", or exceeded at least 50% to 60% of the time according to Florida Administrative Code (a 50%-exceeded goal is used following Richardson 2000, Ware 2001, Hall and Robison 2001). The minimum frequent low level, corresponding to the "semi-permanently flooded" hydroperiod, should be exceeded 80% of the time according to Florida Administrative Code (also Richardson 2000, Ware 2001, Hall and Robison 2001).

For Shaw Lake, two additional minimum levels are established: the "minimum infrequent high" level and the "minimum infrequent low" level. These levels should be exceeded approximately 5% of the time, and 95% of the time, respectively (see Figure 1 in Richardson 2000, Ware 2001, or Hall and Robison 2001).

Simulation results can be compared to the MFLs in Table 7 on a stage-duration graph. Figure 56 (see also Figure 1 in Richardson 2000, Ware 2001, and Hall and Robison 2001) shows the stage-duration relationship implied by the minimum levels for a hypothetical lake (dotted blue line). Also shown are hypothetical simulation results from two long-term (30-year) simulations. In one case (red line) the simulated stage-duration curve lies completely above the minimum-levels curve, meaning that MFLs are met in the simulation and that additional lake water may be available for use. In the other case (green line), the simulated curve lies below at least one of the minimum levels, indicating that MFLs are not met in the simulation.

6.3 Base Case Predictive Scenario

The first predictive scenario is taken directly from the calibrated model, with no adjustments to water use (other than using monthly averages as described in Section 6.1). This base case is a reference for comparing all of the other predictive scenarios. The base case can be thought of as the scenario in which water use does not change substantially in the future.

Figure 57 shows the simulated 30-year hydrographs for SAS wells for the base case. Simulated Floridan well hydrographs are shown in Figure 58. Lake level hydrographs are presented in Figure 59 for this scenario. These three figures show that heads and lake stages vary due to seasonal pumping (Figure 55) and due to changes in rainfall (Figure 54).

Since the last five years of the scenario use precipitation data from 1995-1999, the hydrographs from this period can be compared to the calibration hydrographs (Figures 59, 60, and 61). Three main things are different in the scenario simulation: 1) initial conditions (conditions on January 1, 1995), 2) reduced ET in May 1998 through December 1999 due to use of the averages from Smajstrla and others (1984) rather than the FAWN data, and 3) averaged water use. Due to the ET difference, and due to averaged water use, the ranges of variation in the scenario hydrographs are somewhat reduced, especially for the Floridan wells (the winter lows are less pronounced) and several lakes (the stage drops in 1998-1999 are not as severe).

The stage-duration curves for the base case are presented in Figure 63, along with the established minimum levels from Table 6. Only in the case of Lake Pierson are all minimum levels met in the base case (no change in water use) simulation. However, this does not necessarily mean that the other lakes will not meet MFLs. The calibrated model tends to underestimate the lake stage for Drudy Lake, Lake Emporia, and Shaw Lake (typically by less than 1 foot, see Figure 31). Also, the model hydrographs tend to be flatter than the actual hydrographs (missing some of the peaks and valleys), probably because the model stresses are averaged over months and the lake stages change more rapidly. Furthermore, because of the monthly averages used for water use and PET, the scenario simulations do not reproduce the extreme high levels and low levels that would likely be observed in the future.

Because the simulation misses the highs and lows of the true hydrographs, it is best to look at the minimum average levels (50% exceeded stage) shown in Figure 63. In this case, four of the five meet or nearly meet (in the case of Lake Purdom) the minimum level in the base case scenario simulation. The other lake, Shaw Lake, is already scheduled to have its MFLs reviewed, and possibly lowered, based on the latest guidance for establishing minimum levels.

Lake Pierson and Lake Purdom have flat simulated stage-duration curves, as compared to the other lakes, which indicates that these lakes (in the simulations) have a fairly consistent lake level (also evident in Figure 59). The observed data for Lake Purdom are in fact much less variable than either Lake Emporia or Shaw Lake (Figure 25). When Lake Purdom was investigated for setting minimum levels (Neubauer 1994), it was noted that this lake “has a remarkably stable water level compared with many other lakes in the Crescent City-Deland Ridge.” The observed calibration data for Lake Pierson (Figure 25) do not cover the dry years of 1998 and 1999, so the model may or may not be accurate for low-stage events at that lake.

According to the District’s water-budget lake models, Lake Pierson is the only lake that is meeting MFLs with excess capacity. That is consistent with the results of this model scenario. The water-budget models suggest that Drudy Lake and Lake Emporia are just meeting MFLs, and that there is no capacity for further withdrawal (similar to the results of the lake-groundwater model). For Shaw Lake, the District intends to revise the minimum levels. Recent revisions made for Lake Pierson (Hall and Robison 2001), Drudy Lake (Ware 2001), and Lake Emporia (Richardson 2000) resulted in lower, more easily attained, minimum levels (with one exception – the minimum frequent high level for Lake Emporia was raised during reevaluation). A similar revision for Shaw Lake would mean that the simulated stage-duration curve would be above minimum levels. The District’s water-budget models have not been used to assess whether or not minimum levels are currently being attained for Lake Purdom.

6.3.1 Impacts of Long-Term Wet and Dry Conditions

Figure 64 shows simulated lake stages for two-year periods of high rainfall (1991-1992, with a total of 123 inches of rainfall) and low rainfall (1998-1999, with a total of 78 inches of rainfall) that occur during the base case scenario. These plots indicate the effect of extended wet and dry periods on lake levels (water use is identical in the two periods).

The overall effect of an extended wet period is to raise lake stages, and the effect of an extended drought is to lower lake stages. The simulations indicate that Shaw Lake is most affected by extreme climatic events, and that Lake Pierson and Lake Purdom are affected least. The total lake stage change during the two-year climatic extremes is about 4 ft for Shaw Lake, 2.5 ft for Drudy Lake, 2 ft for Lake Emporia, and 1 ft or less for both Lake Pierson and Lake Purdom.

6.3.2 Correlation between Aquifer Heads and Lake Levels

Lake levels and surficial aquifer heads respond similarly to wet and dry periods and to increases or decreases in pumping rate. It is therefore expected that there is a correlation between simulated lake stage and simulated SAS levels. Figure 65 shows the relationship between simulated lake levels and the simulated head at hypothetical SAS observation wells within a few hundred feet of the lake shores (Figure 22).

The trend lines and coefficients of determination (R^2 values) shown in Figure 65 indicate a few things. First, the correlation is not always strong (R^2 ranges from 0.28 to 0.78), indicating that factors such as runoff, stream outflow, and non-uniform irrigation patterns influence results substantially. The slope of the trend lines range from 0.14 for Pierson Lake to 0.88 for Shaw Lake. The slopes are smaller for Pierson Lake and Purdom Lake because the stages of these lakes are less variable than the others. The heads in the observation wells have greater ranges of variation than the corresponding lake stages.

6.4 Effect of Increasing or Decreasing Water Use

Several additional 30-year simulations were made with hypothetical changes in water use. These changes reflect potential future water demand changes brought about by changes in crop production, irrigation practices, or permit limits.

First, a model-wide 25% increase in water use was simulated (including all agricultural permits and the Pierson public supply permit). The resulting lake stage-duration curves are shown in Figure 66. Interestingly, only Drudy Lake and Shaw Lake are substantially affected by the increased withdrawal – each is lowered by about a foot at almost all percentiles. For the other lakes, the stage decrease is less than one inch and the two lines in Figure 66 appear as one. For the three lakes that show little response to pumping, net groundwater seepage into the lake increases in the scenario because net recharge (partially from irrigation) and SAS heads go up. Also, for Lake Pierson and Lake Purdom, the very small stage decreases lead to substantial decreases in stream outflow, helping to balance the increased direct removal of lake water.

The numerical model result for the lakes is consistent with the conceptual model. When additional water is withdrawn from groundwater, heads decrease (especially in the UFA but also elsewhere). But that water is added back to the surface-water/groundwater system as irrigation. Some of the added irrigation reaches the SAS as added recharge causing heads to rise in many places in this aquifer. The stage of Shaw Lake drops because that lake is well connected with the Floridan Aquifer, where heads decrease most due to increased pumping. Lake Drudy is the smallest of the five lakes of interest, it has the highest total direct lake withdrawal rate (Figure 19), and it has the smallest watershed and runoff inflow (Figure 18). These factors explain why there is a response at Lake Drudy when withdrawals increase, even though there is very little response at some other lakes.

For a 25% reduction in water demand (Figure 67), the results are almost exactly opposite of the 25% increase. The stages of Shaw Lake and Drudy Lake go up by about a foot, and the other lakes are unaffected.

If the 25% increase and 25% decrease are applied only at agricultural permits around the lakes, the results are similar (Figures 68 and 69). In these simulations, only the permits associated with land areas in the lake watersheds were modified (see Figures 14 and 18). Compared to the model-wide demand changes, the effects of the limited-area demand changes are slightly less for Shaw Lake, and about the same for Drudy Lake.

6.5 Effect of Minimizing or Maximizing Withdrawal from Surface Water

About half of the agricultural water-use permits in the model have both groundwater wells and surface-water pumps. For these permits, the model can simulate any percentage breakdown between surface-water use and groundwater use.

In one simulated scenario, the amount of water use from surface water was maximized. This resulted in fewer groundwater withdrawals, but more direct withdrawals from the lakes of interest. The resulting stage-duration curves are compared to the base case in Figure 70. The stage of Drudy Lake, which is the smallest and most heavily pumped lake (Figure 19), drops most significantly (about 2 feet). The Lake Emporia stage also decreases a little (less than 1 foot). Lake Pierson and Lake Purdom are again unaffected. Interestingly, the stage of Shaw Lake actually increases when withdrawals are shifted to surface water sources. This happens because Shaw Lake is well connected to the UFA and UFA heads go up in response to the regional decrease in groundwater withdrawal. The increasing-stage effect of the UFA response on Shaw Lake more than offsets the decreasing-stage effect of increased direct withdrawal.

In the opposite case – minimum surface water withdrawal and maximum groundwater withdrawal – lake levels go up at Drudy Lake and Lake Emporia and down at Shaw Lake (Figure 71). Again, Lake Pierson and Lake Purdom are unaffected.

6.6 Predictive Analysis Assessment

The predictive scenarios and simulated stage-duration curves presented in this section indicate that some lakes are more sensitive to climatic and water-use changes than others. In the simulations presented, Lake Pierson and Lake Purdom have relatively flat stage-duration curves and are least affected by changes in rainfall or changes in water use. These lake levels are predicted to be relatively stable over the long run. The stable lake levels for Lake Pierson and Lake Purdom can be partially attributed to the representation of significant stream outflows for these lakes (small stage changes can significantly change the lake water budget because of the stage-discharge relationships). Shaw Lake and Drudy Lake (and to some extent Lake Emporia) are more sensitive to changes in climate and water use. Shaw Lake's sensitivity is primarily the result of its good connection with the underlying UFA. Drudy Lake is sensitive because of its small area and relatively high direct withdrawals.

A couple of particularly interesting results were noted in this predictive analysis. The first was that only two of the five lakes (Shaw and Drudy) showed any sensitivity to overall changes in water use (total water demand from both surface water and groundwater). The other three lakes have negligible stage decreases when pumping is increased because the SAS heads rise in response to increased irrigation and/or because stream outflows stabilize lake levels. The other interesting result was that simulated stages increased for Shaw Lake when surface-water withdrawals were maximized (groundwater withdrawals minimized). This happens because Shaw Lake is in good connection with the UFA, and UFA heads increase when groundwater withdrawal decreases.

The results for these simulations indicate that the model is not an ideal predictor of future lake stages and future stage-duration relationships; however, they do help with the understanding of lake-groundwater interactions and the relative effects of future changes on these interactions. The base-case predictive scenario (no change in water use) seems to indicate that four of the five lakes will not meet all of their minimum levels. However, this result must be interpreted with discretion because the model tends to under-estimate lake stage at some lakes and it cannot capture the extreme high and low stages accurately. It is most reasonable to compare only the minimum average level to simulation results. Four of the lakes are at or above this level, and the fifth – Shaw Lake – has been flagged for MFL reevaluation.

According to the simulations, lake stages can increase or decrease by as much as 4 feet in 2 years due to wet or dry conditions, even when water use is not changed. Reducing the overall water use by a substantial amount (approximately 25%) can raise the stages of Shaw Lake and Drudy Lake by about 1 foot. The Shaw Lake stage increases when UFA pumping is reduced.

7.0 CONCLUSIONS

The lake/groundwater model developed here simulates the environmental processes that affect lake levels and aquifer heads. The model is qualitatively calibrated to observed heads in twelve observation wells and observed stages at the five lakes of interest, for the period of 1995 through 1999. Once calibrated, the lake/groundwater model is used to show the effects of potential future water-use scenarios. The lake levels and groundwater heads respond to changes in climate and changes in water withdrawal. Increased water withdrawal leads to lowered heads in the Floridan

Aquifer. Because the withdrawn water is added back to the surface-water/groundwater system as irrigation, the lake levels and SAS heads may go up, down, or remain the same when withdrawals increase, depending on various conditions.

The model presented in this report uses the groundwater simulator MODFLOW (Harbaugh and McDonald 1996), with the Lake Package (Council 1999) to model lake/groundwater interaction. Runoff and net groundwater recharge are analytically calculated from precipitation data, irrigation estimates, and minimum and maximum ET estimates. Future scenarios are simulated for thirty years using measured precipitation from 1970-1999 as a surrogate for future precipitation and estimated monthly averages for other model inputs. The lake level results for the thirty-year scenario simulations are compared with stage-duration curves.

In the model, many assumptions and simplifications of real-world processes are made. These assumptions and simplifications are necessary because of limited data, incomplete understanding of physical processes (e.g., ET), and unavailability of widely accepted methods for modeling complex processes. As a result, the applicability of model results is limited. It is recommended that the model be used to show the relative effect of certain changes (in water use or precipitation, for example), rather than relying on the model results to accurately predict future conditions. Not only are calibration model results inexact replications of past events, but also the scenario simulations are based on estimates of future conditions that are, at present, unknowable.

Specific and potentially important simplifying assumptions made for this model include:

- simplification of unsaturated-zone processes to a water-balance equation,
- application of the empirical SCS curve number method for runoff,
- no accounting for the storage effects of lakes and wetlands (other than the lakes of interest),
- simplified representation of ET, and
- assumption of constant land use.

Evapotranspiration is an important process in this model. Data to more accurately define the time-variability and space-variability of ET are unavailable and would be difficult to obtain from field tests.

Also, monthly averages are used in the model for important model inputs such as precipitation, runoff, PET, and water use. This averaging causes the model to under-predict the magnitude of short-lived climatic and water-use events (e.g., changes due to storms, pumping for frost/freeze protection).

Still, the model presented here incorporates the general effect of many environmental factors – precipitation, evapotranspiration, well withdrawal, etc. – in a manner that is consistent with the conceptual model of lake/groundwater flow, the accuracy of available data, and the overall goals of the project. If the model limitations and assumptions are kept in mind, then the model can be a useful tool for evaluating the future response of the lake and groundwater flow systems to postulated conditions. While the exact magnitude of predicted heads, lake stages, and flow rates will not always be accurate, the relative effect of one scenario vs. another should be valid. This information should be useful to water planners when devising management policies for the area.

Due primarily to averaging of time-variable model inputs into monthly values, the scenario simulations tend to understate the variability of lake levels (simulated stage-duration curves are flatter than they would truly be). As a consequence, it is unadvisable to draw strong conclusions from a comparison of simulated results to established minimum levels. The best level to use for comparison is the minimum average level, which is met (or nearly met) at four of the five lakes of interest in the base-case scenario.

An interesting result from the scenario simulations is that changes in water use (by up to 25%) have very little effect on the levels of three of the five lakes of interest (Lake Pierson, Lake Emporia, and Lake Purdom). Drudy Lake is affected by water-use changes because of its small size and higher direct withdrawal rates. Shaw Lake is well connected to the UFA and therefore the stage at Shaw Lake responds more strongly to changes in UFA pumping.

8.0 RECOMMENDATIONS

The numerical model is a practical implementation of the current conceptual model of surface-water/groundwater flow in the Pierson area. In addition to providing quantified results consistent with the conceptual model, the model can be used to develop ideas for future field testing and data collection. For instance, additional data on the interaction between wetlands, lakes, streams, and aquifer (e.g., flow measurements, localized pumping tests) could help refine the conceptual model and improve the numerical model application.

The results of this model indicate that two of the five lakes (Lake Pierson and Lake Purdom) are controlled in large part by the stream outlet conditions. In general, it is helpful to accurately understand the importance of stream outflow on a lake's water budget. This information can be obtained from contemporaneous measurements of lake stage and outlet stream flow under various conditions (high flow, low flow).

The simple analytical methodology used for runoff and unsaturated zone flow could be made more complex. At a minimum, spatial and temporal variations in the processes could be more accurately accounted for, including consideration of unsaturated zone storage. One fairly simple way to accomplish this would be to develop a package for MODFLOW to handle the analytical calculations used to calculate net recharge. A major advantage of this approach would be that net recharge could be updated daily rather than monthly.

It is not recommended that a full groundwater/surface-water model (modeling the physics of overland flow, open channel flow, and unsaturated zone flow in addition to saturated zone flow and lake flow) be developed for the Pierson Area at this time. Such an endeavor would require much more data than is currently available for model construction and model calibration. The required level of effort for modeling would also be high, and it is unlikely that the additional effort would lead to significantly more accurate results or different conclusions.

Uncertainty in model results could be quantitatively defined (in terms of confidence intervals) through a Monte-Carlo uncertainty analysis using assumed ranges and distributions for parameter values, and perhaps considering alternative conceptual/numerical descriptions of certain processes. The results of such an analysis could indicate the likelihood of observing a given stage change at each modeled lake under different water-use scenarios.

MFLs are typically based on observed soil and plant characteristics. The methodology is consistent with the goal of MFLs – namely, to protect habitat. Model results that estimate prevailing stage-duration relationships can be inaccurate and are not a good substitute for direct observation of field indicators. However, simulated stage-duration curves can be used to make preliminary estimates of minimum levels if no field observations have been conducted. When model results are used for this purpose, it is important to make a long-duration (e.g., 30 year) simulation to cover the range of climatic conditions that would be expected. It is also important to recognize that the simulation is unlikely to capture extreme high-stage and low-stage conditions if precipitation, runoff, and/or water use are averaged over periods of weeks or months.

The effects of a proposed permit modification or additional water-use permit in the Pierson Area can be evaluated using the model presented here. The results can be one piece of information used in the permit review process. The results of a permit evaluation scenario will indicate the likely lake level declines for the five lakes due to the proposed withdrawal. For a particular lake, if the predicted decline is substantial and there is little or no excess capacity above MFLs, then the permit may need to be modified or denied.

The modeling procedure used here for the Pierson area could easily be adapted to other locations within the St Johns River Water Management District and beyond. The procedure would involve refinement of the conceptual model to describe the new area, gathering available data, converting the data to a MODFLOW grid, and making simulations. The results would indicate, among other things, whether the stages of certain lakes are likely to decline if water use increases. The procedure would be easier to implement if the water-budget calculations for net recharge were incorporated into a MODFLOW package as described above.

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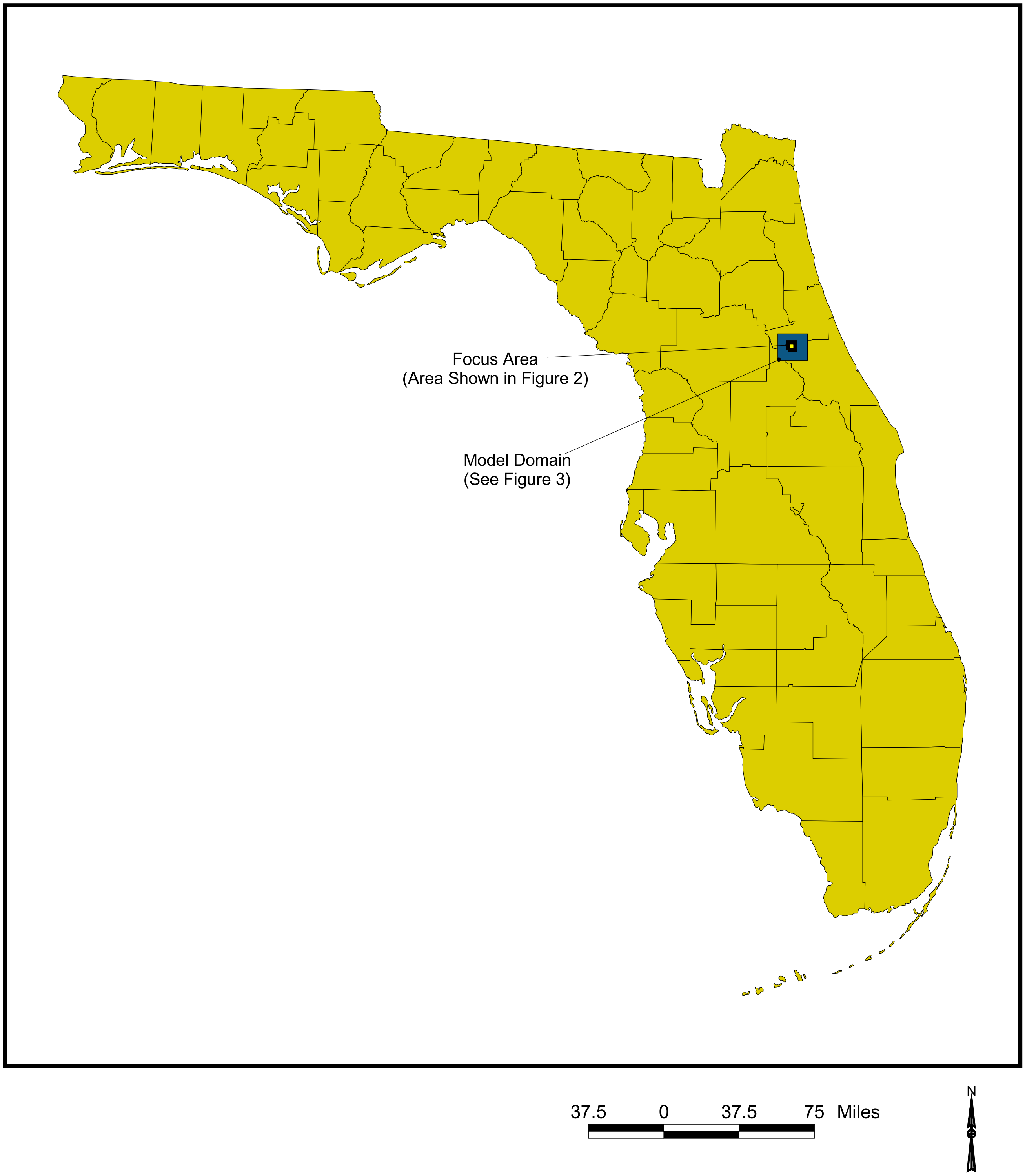


Figure 1. Location of the Study Area

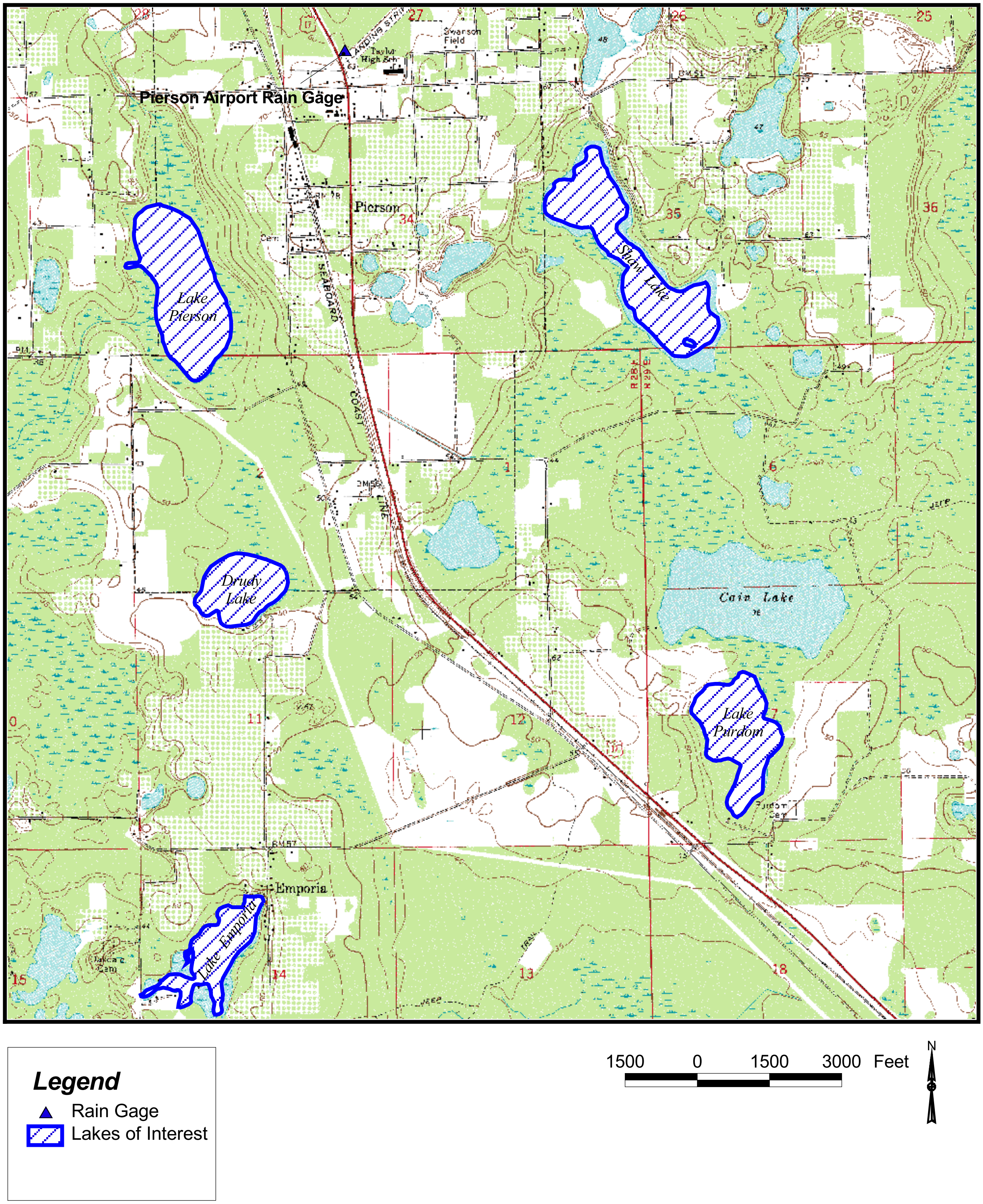


Figure 2. Lakes of Interest

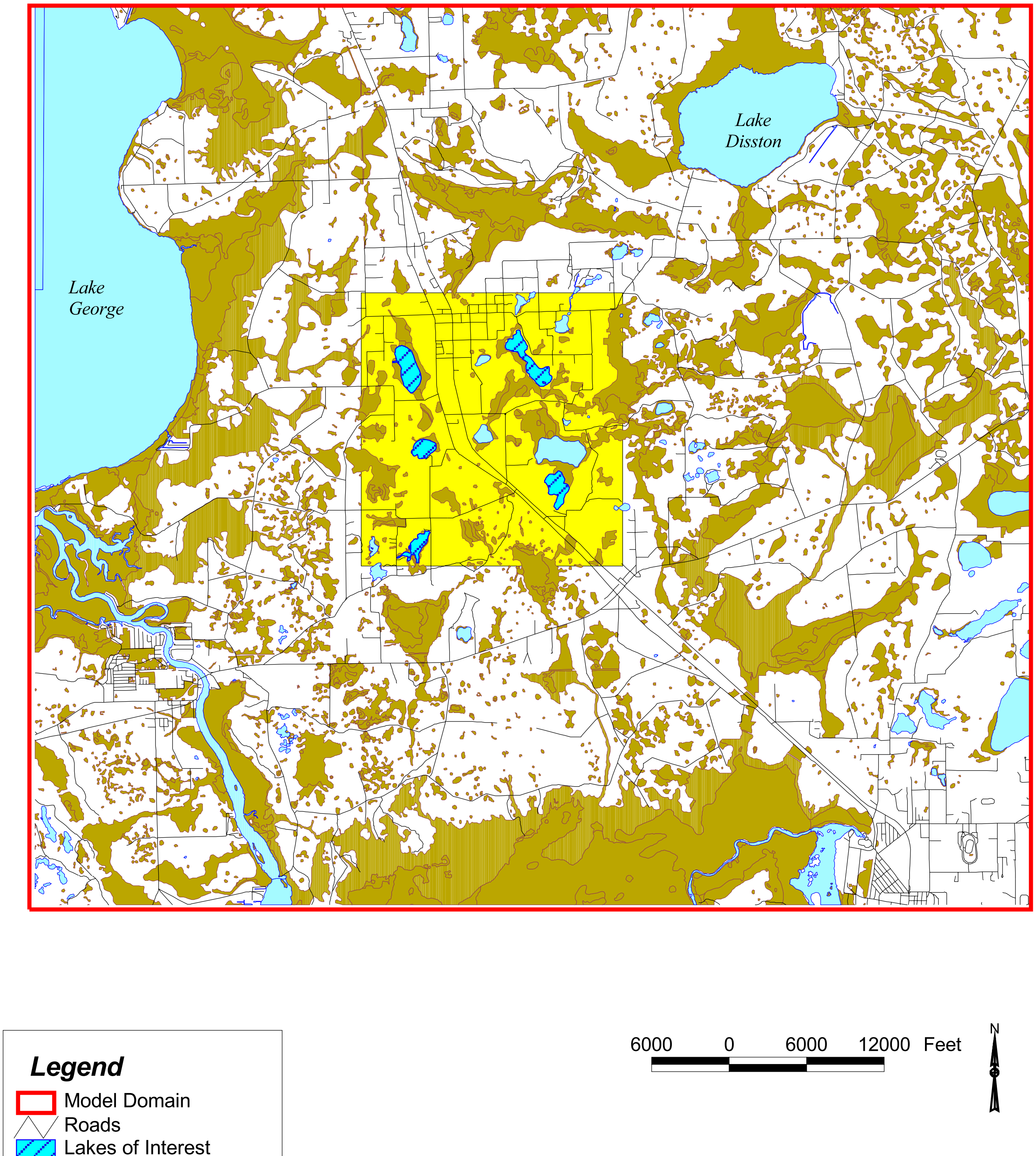


Figure 3. Model Area and Focus Area

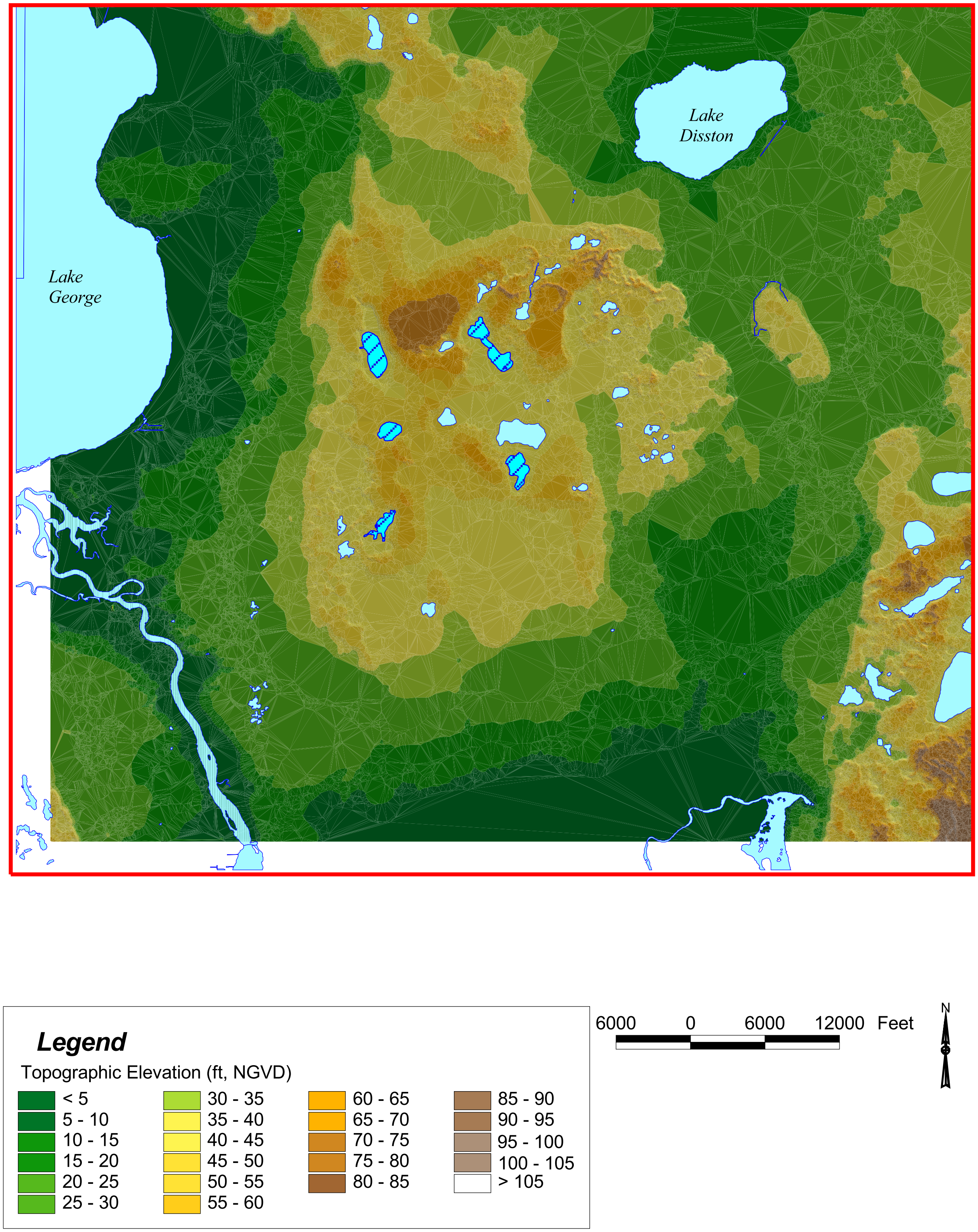
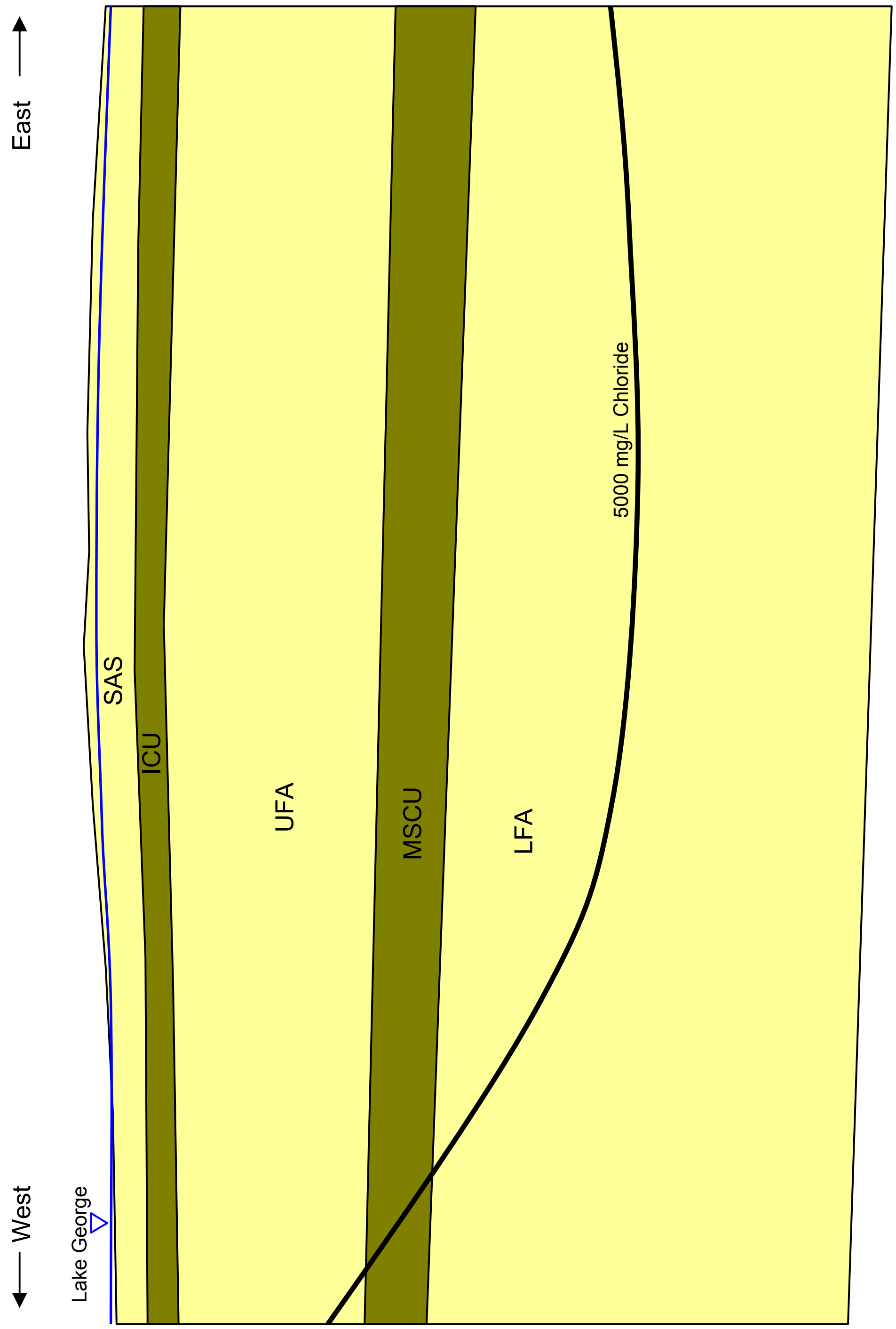


Figure 4. Topography



(Not to Scale)

Figure 5. Generalized Hydrostratigraphy

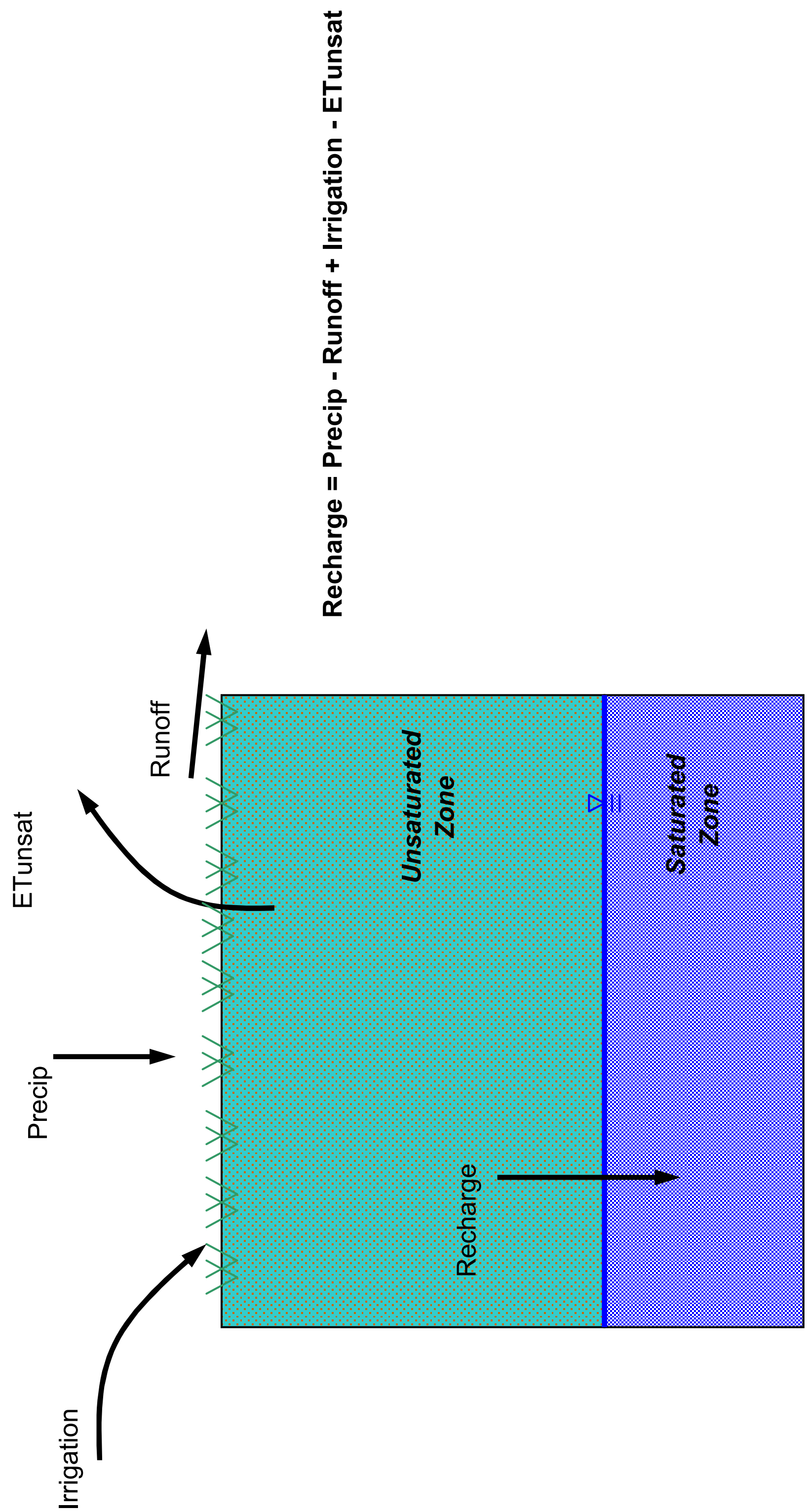


Figure 6. Conceptualization of Groundwater Recharge

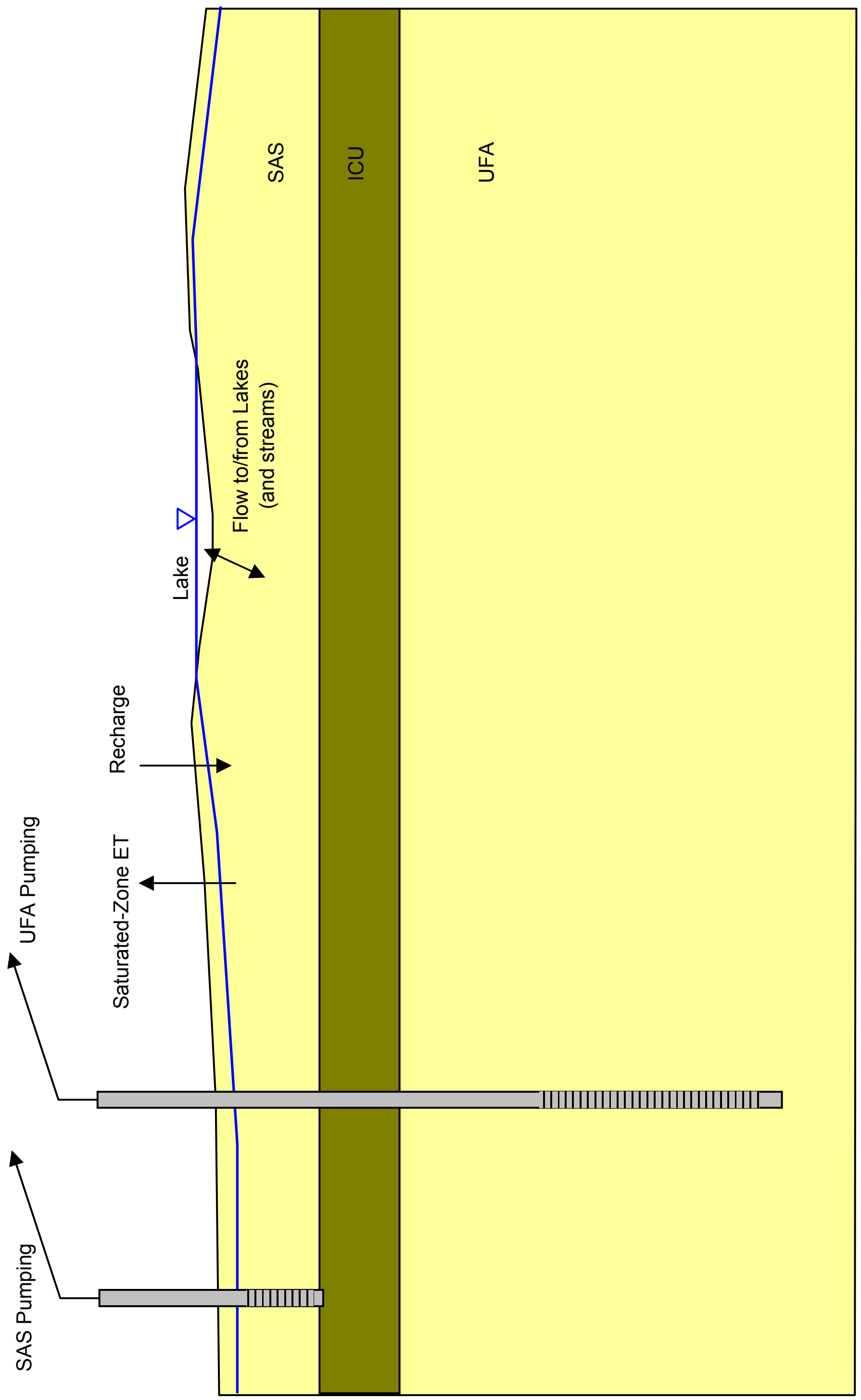


Figure 7. Conceptualization of Groundwater Sources and Sinks

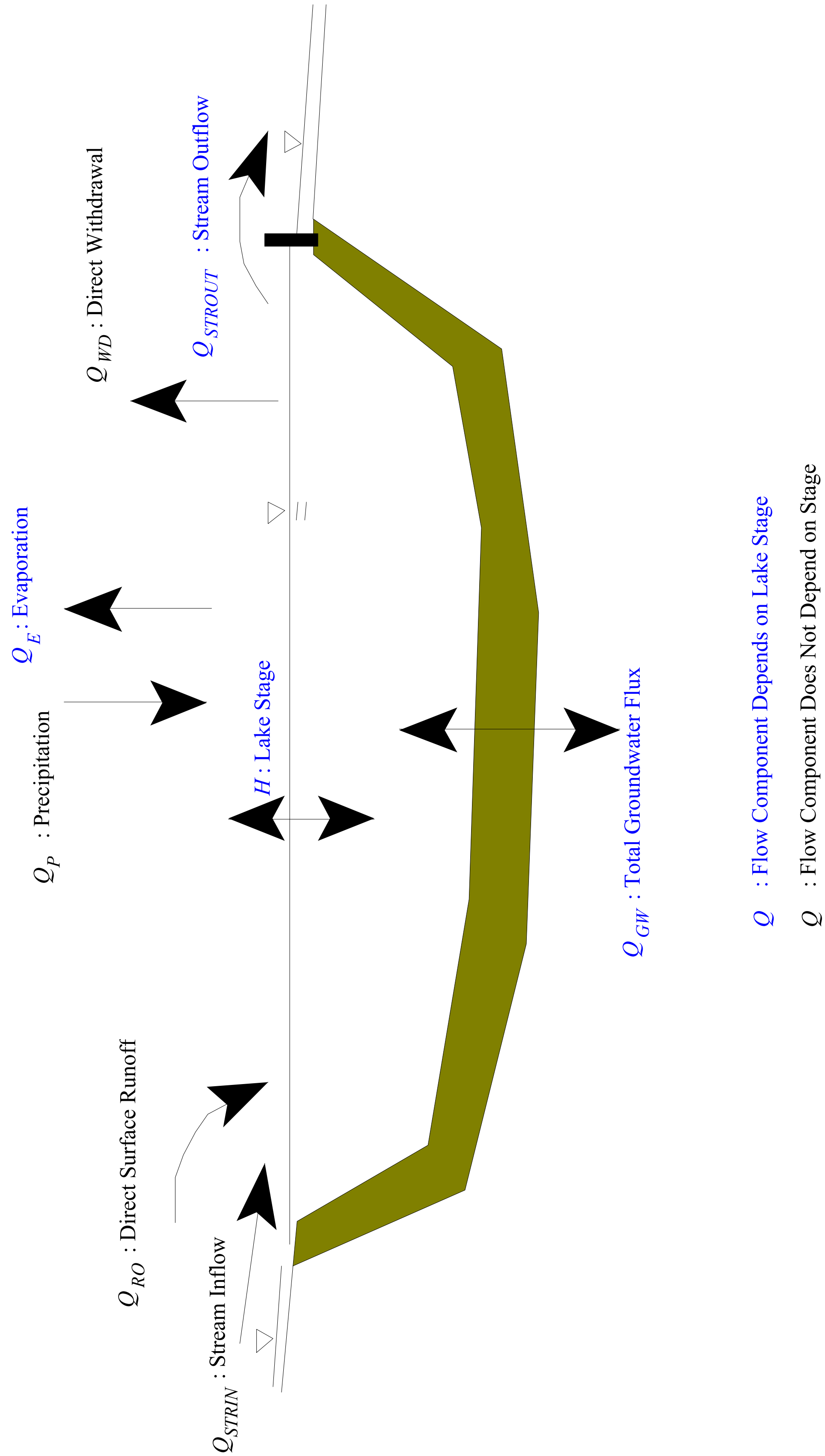


Figure 8. Lake Water Budget

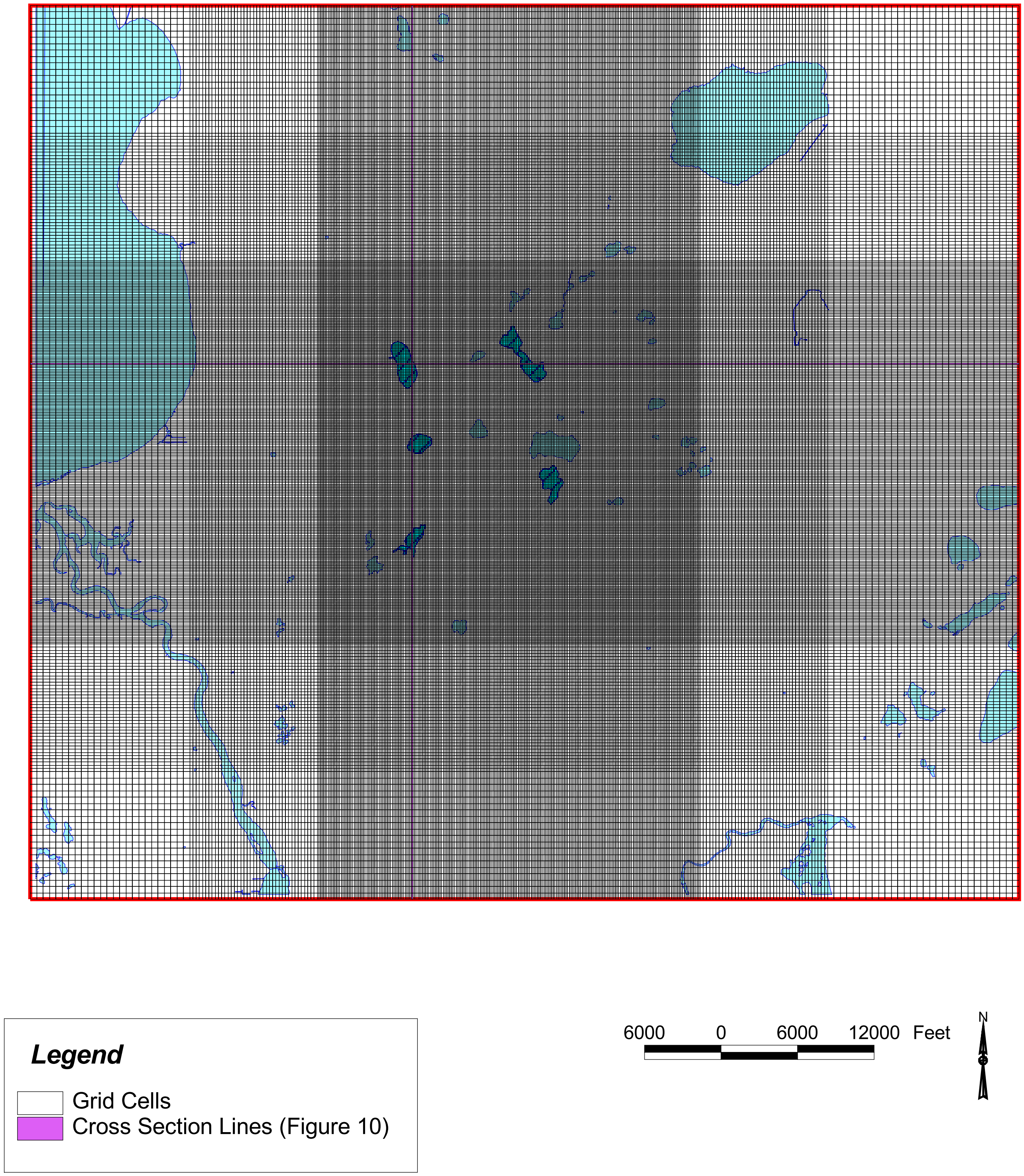


Figure 9. Model Grid

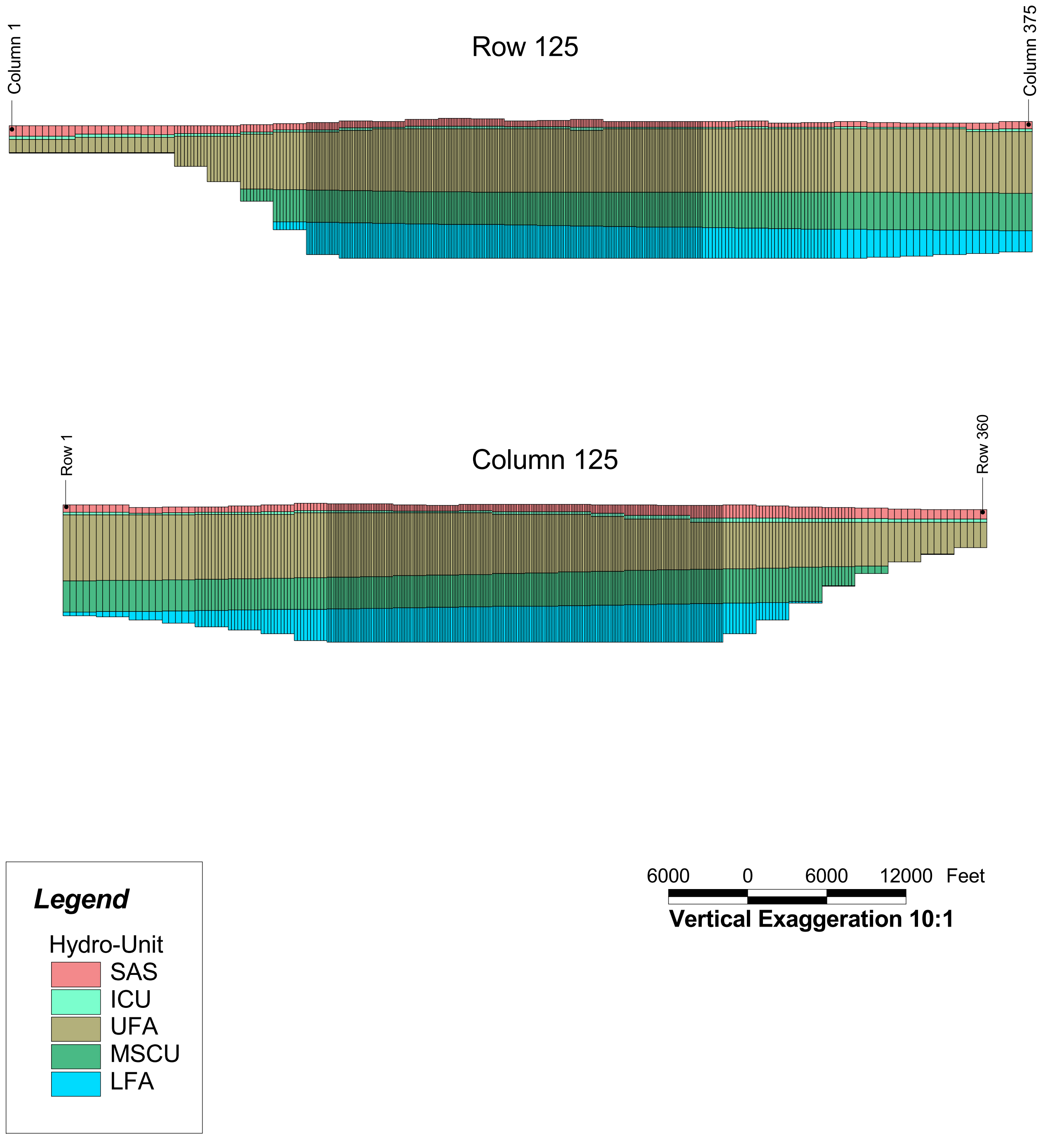


Figure 10. Model Cross Sections

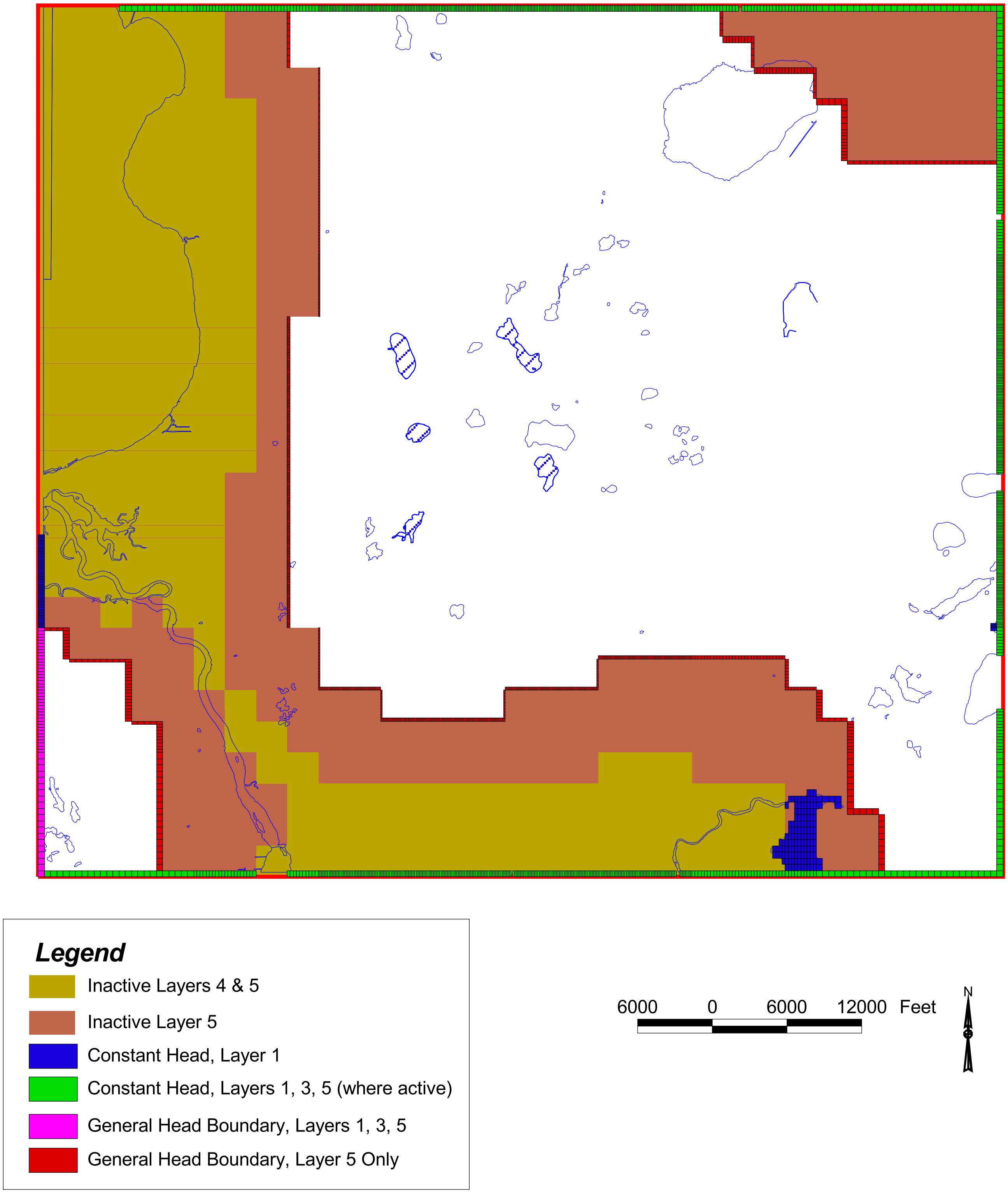


Figure 11. Inactive Areas and Specified-Head Boundaries

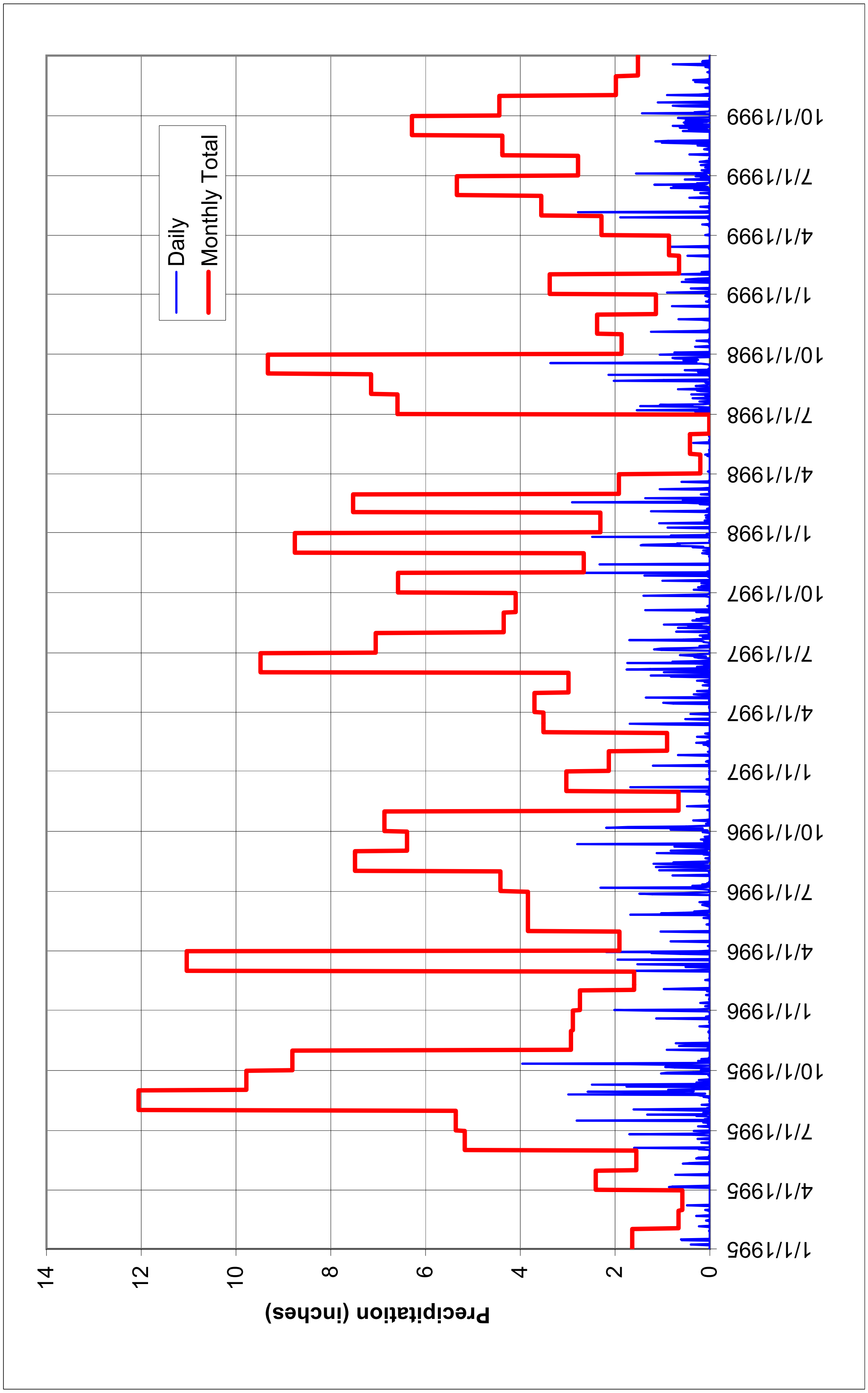


Figure 12. Precipitation at Pierson Airport, 1995-1999

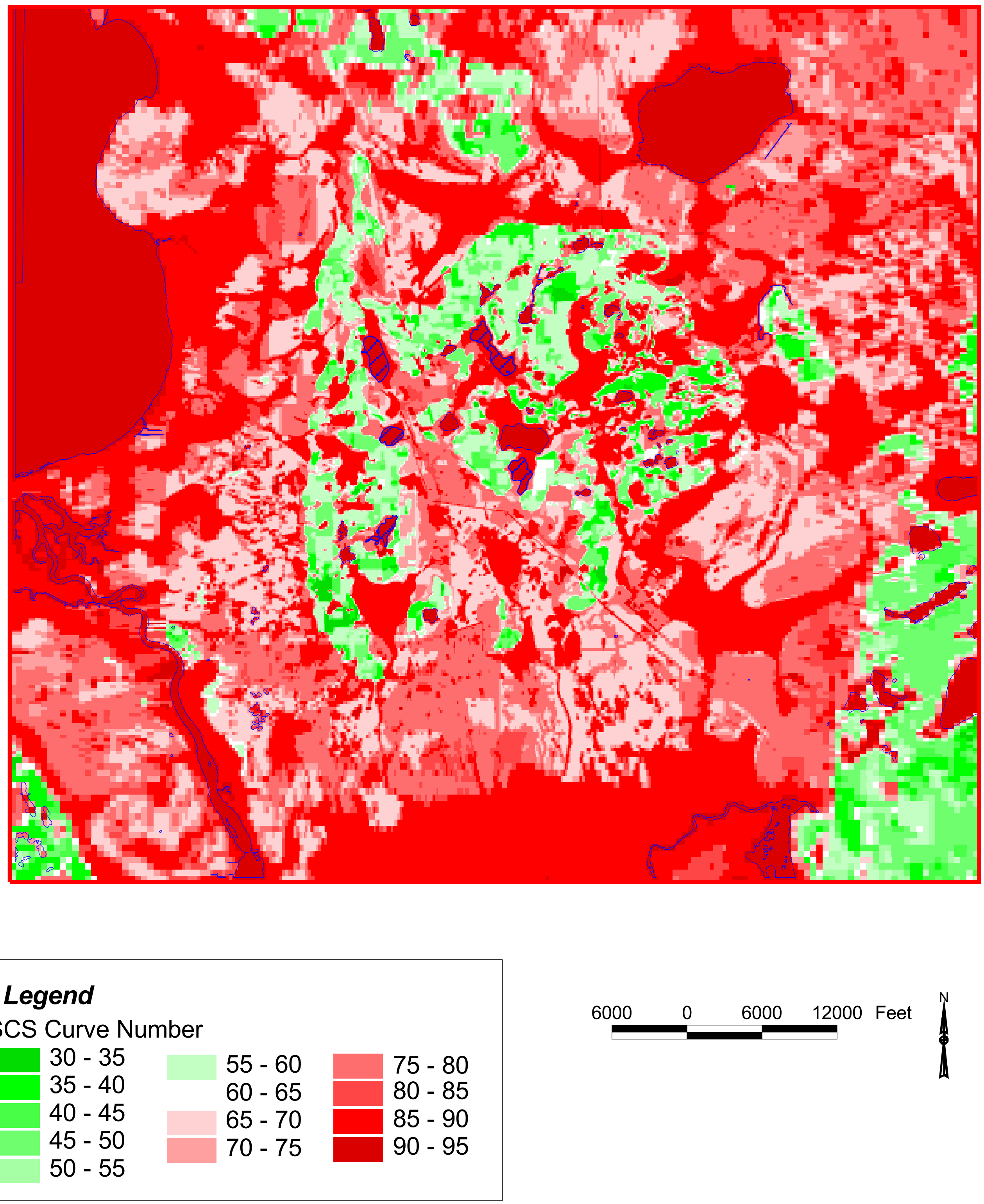


Figure 13. SCS Runoff Curve Numbers

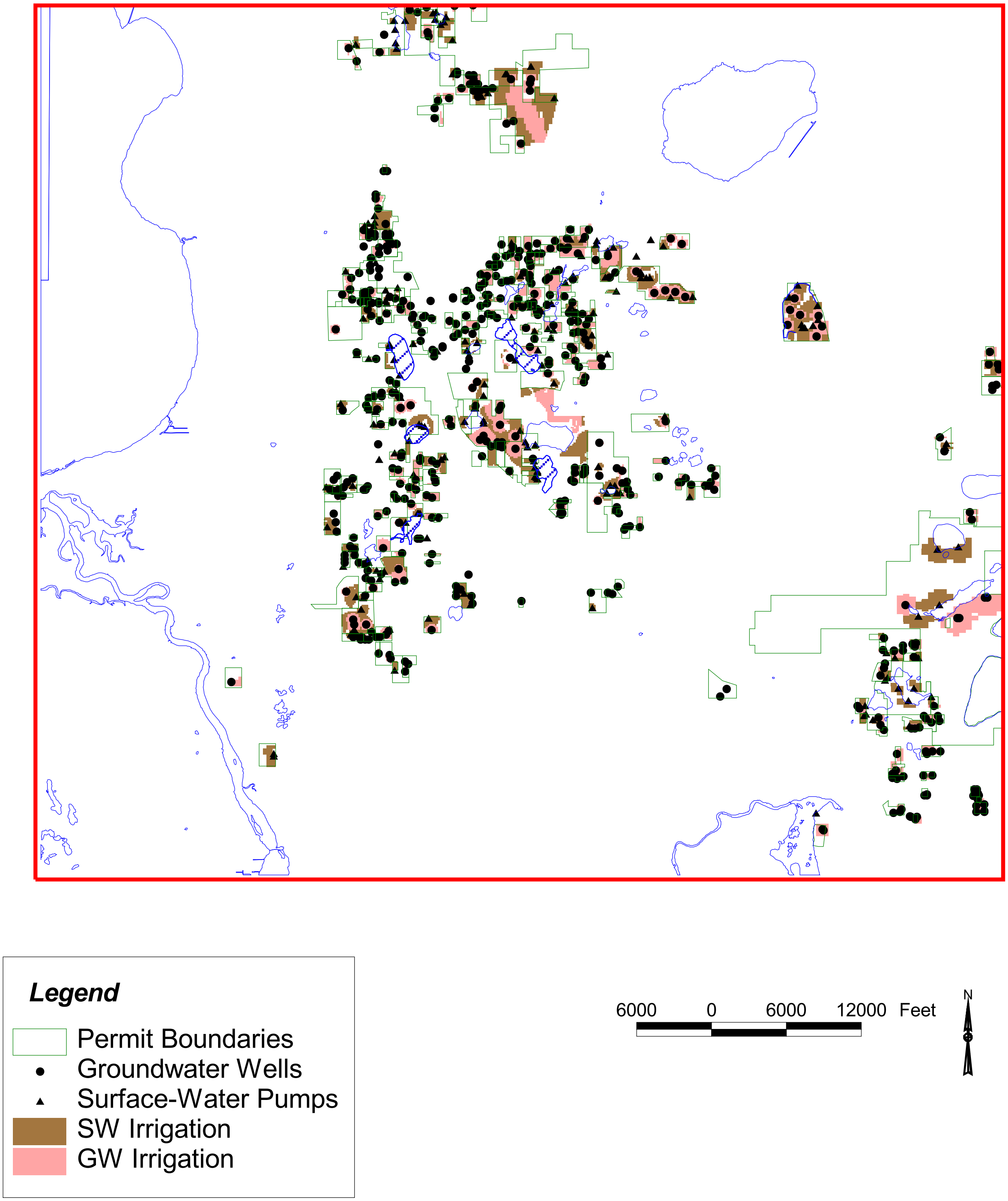


Figure 14. Withdrawal Points and Simulated Irrigation Areas

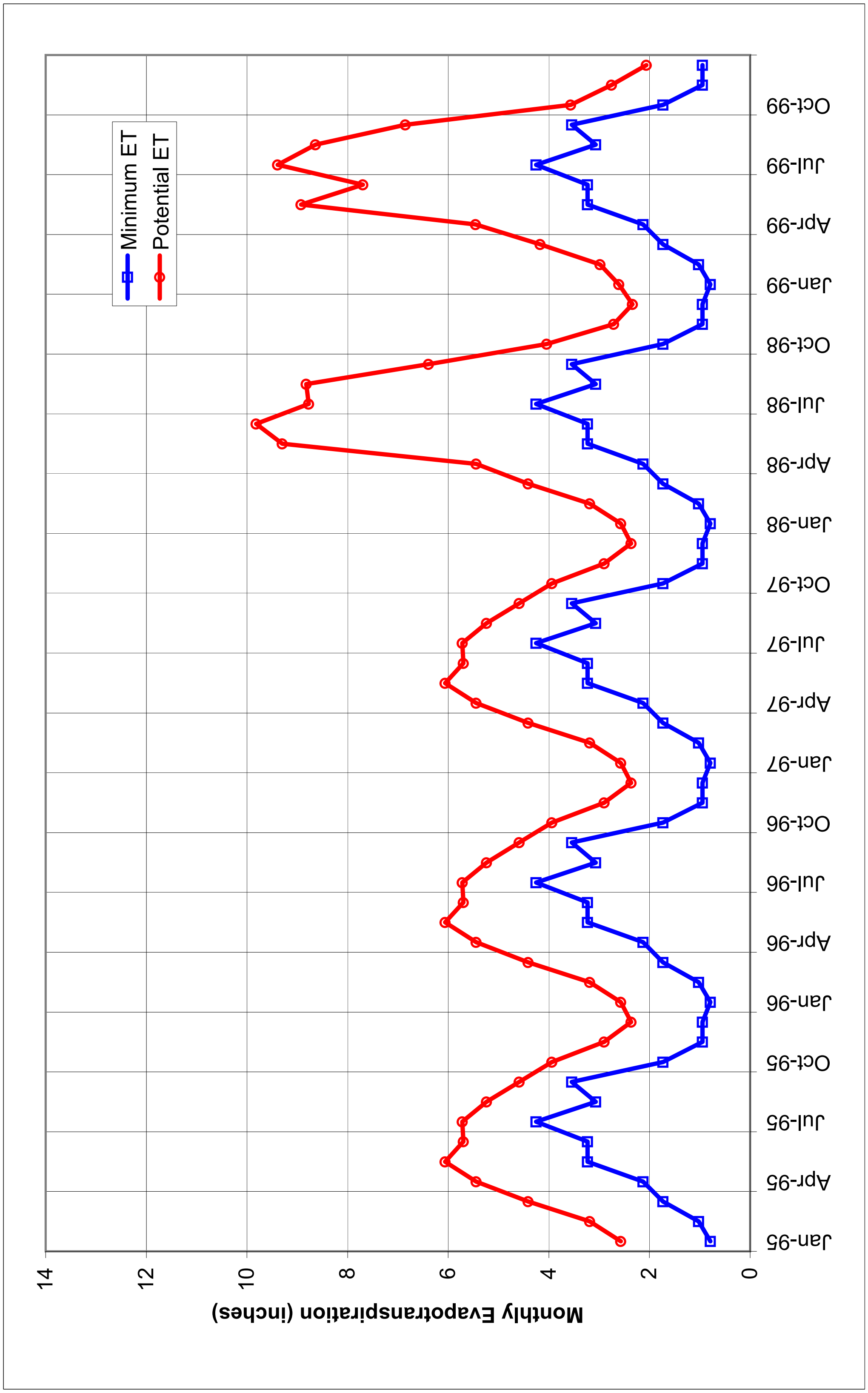


Figure 15. Minimum Evapotranspiration and Potential Evapotranspiration

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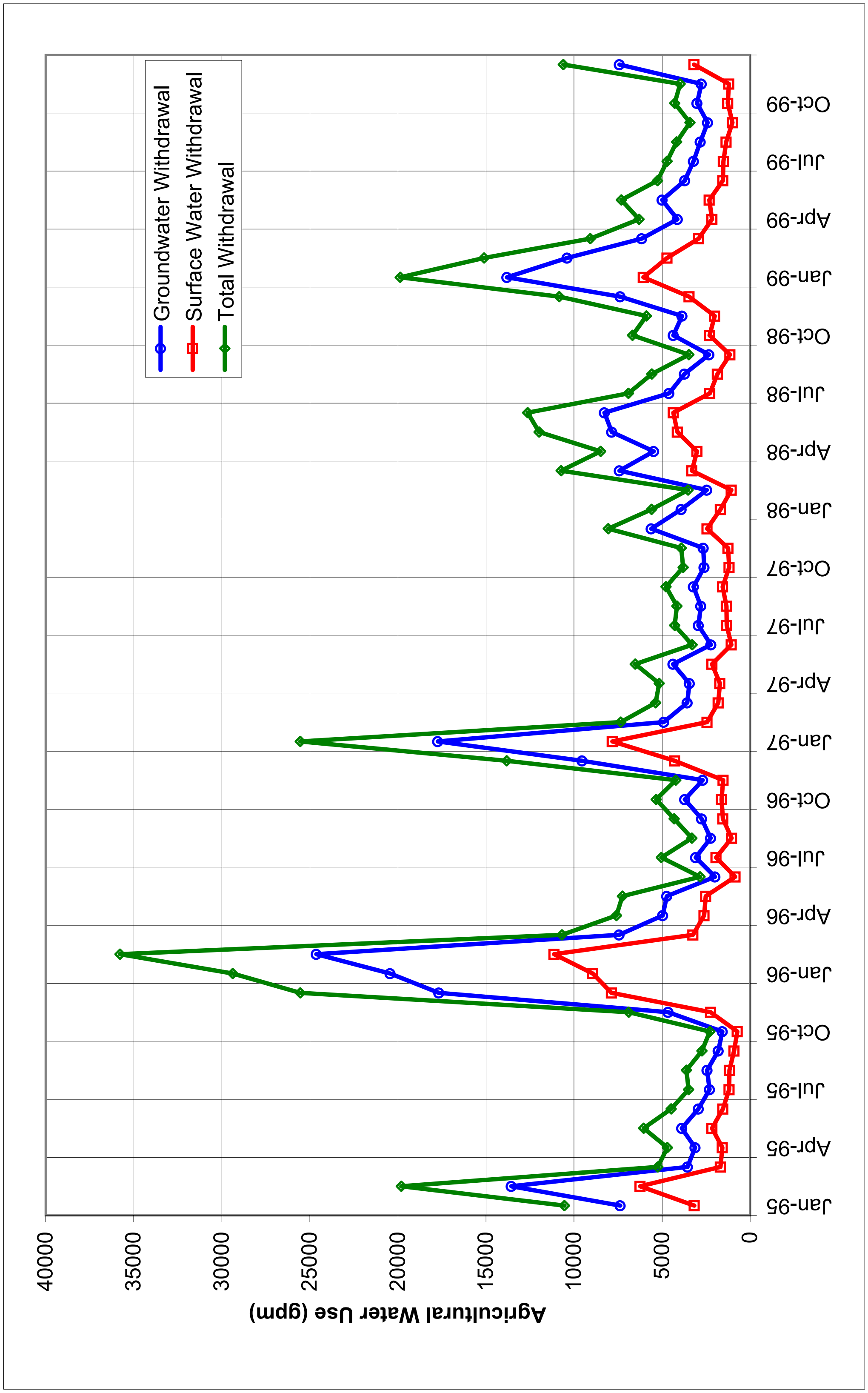

Figure 16. Estimated Agricultural Water Use

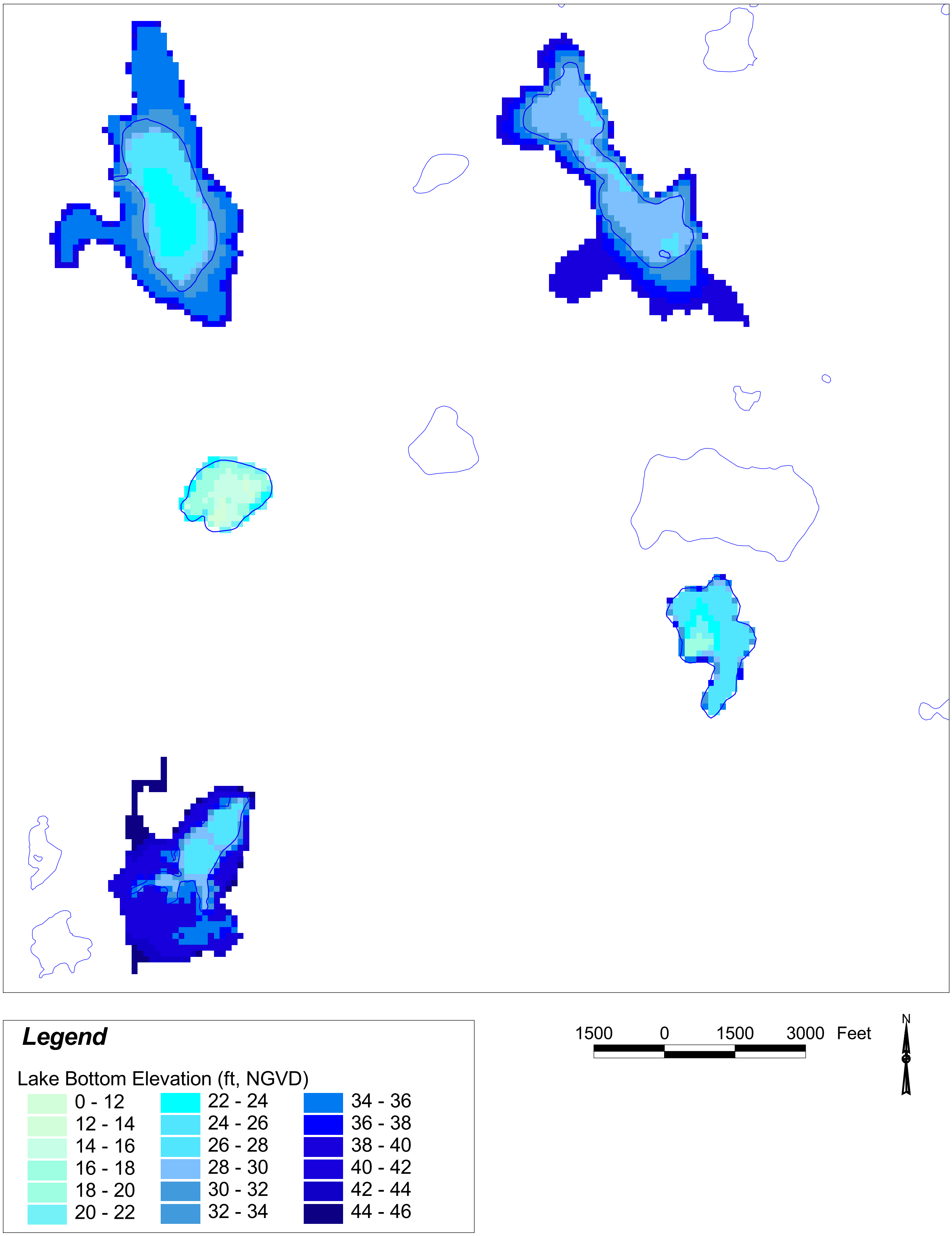

Figure 17. Lake Cells and Lake Bathymetry

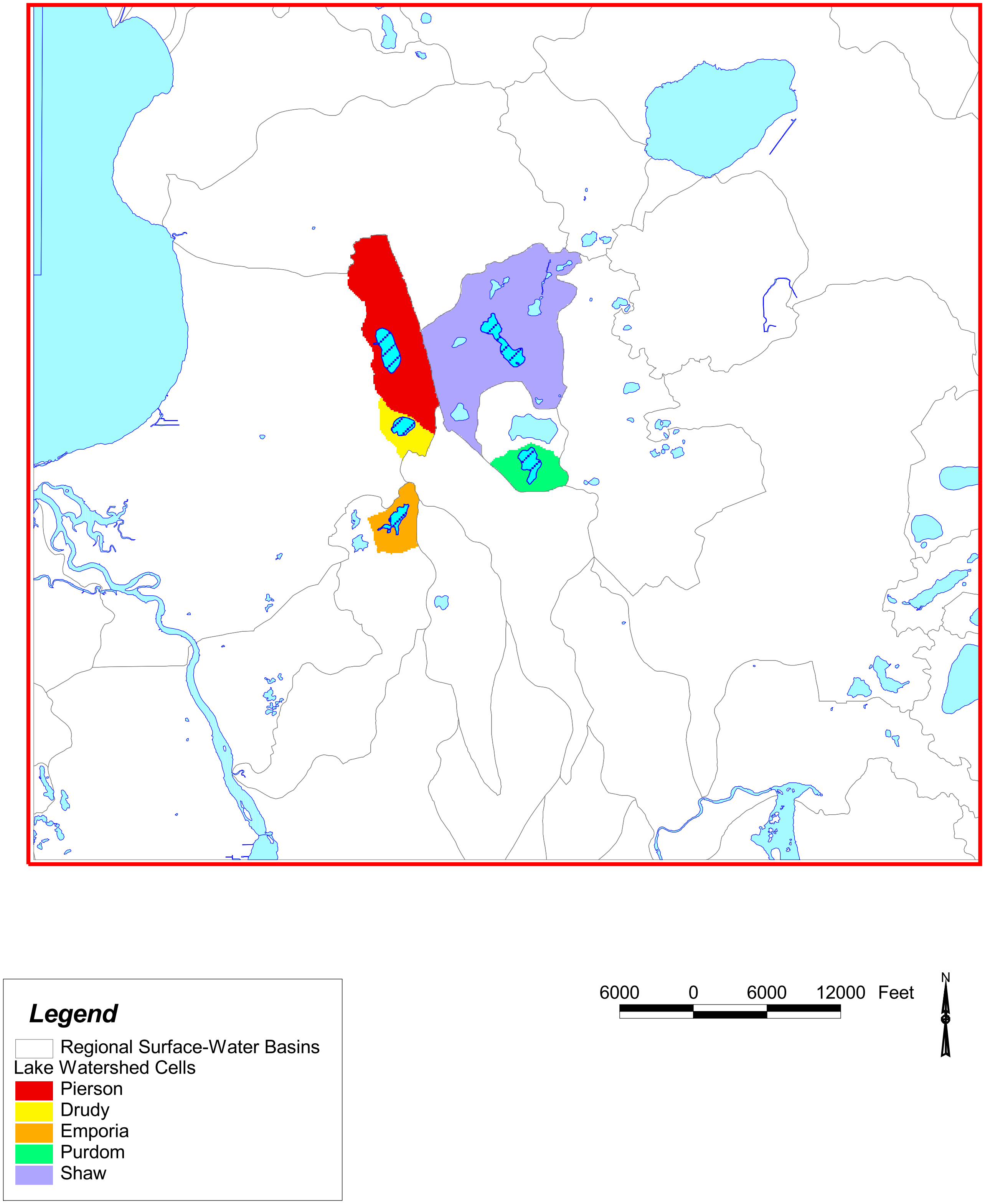

Figure 18. Surface-Water Basins for the Lakes of Interest

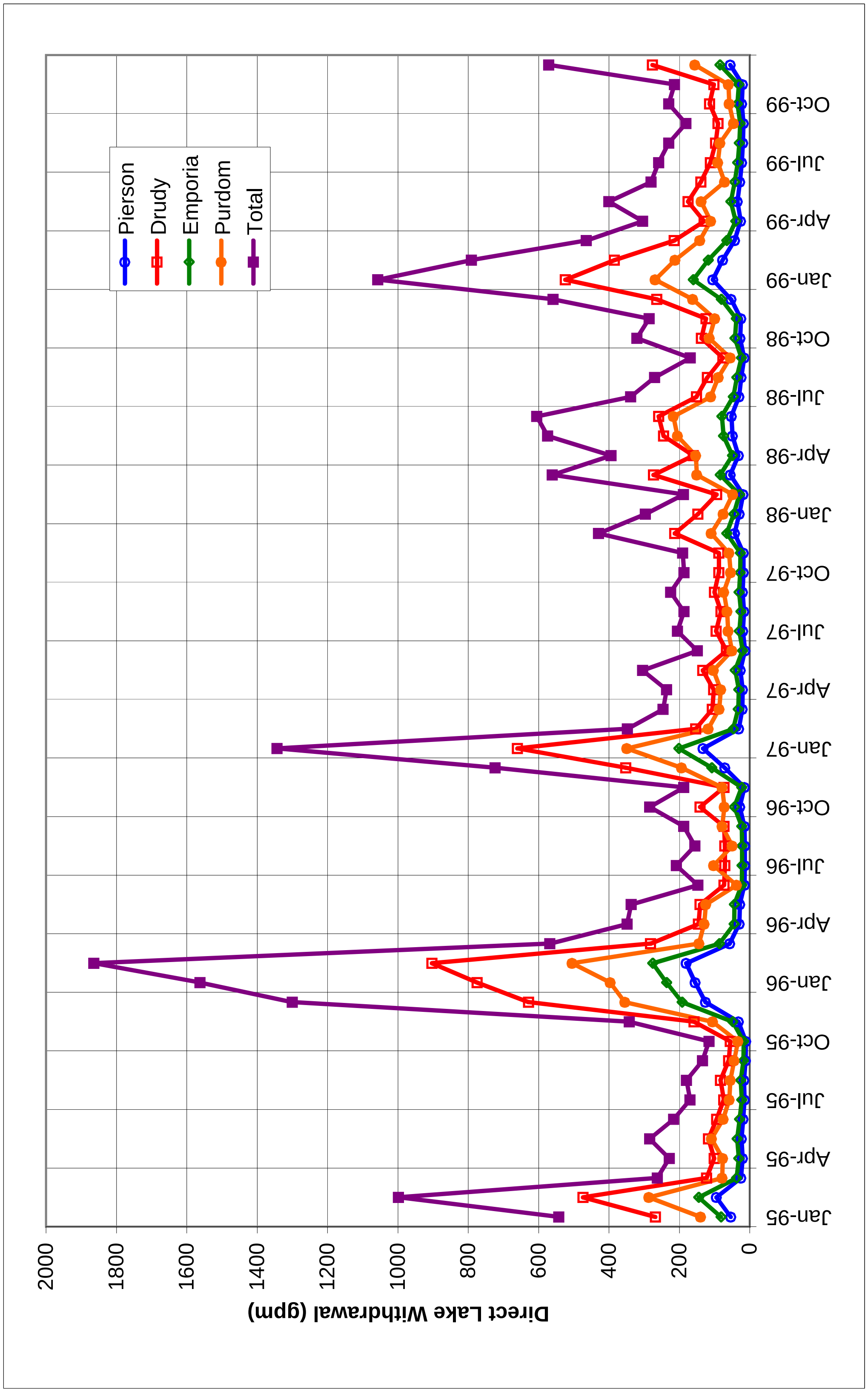

Figure 19. Direct Withdrawal from Lakes

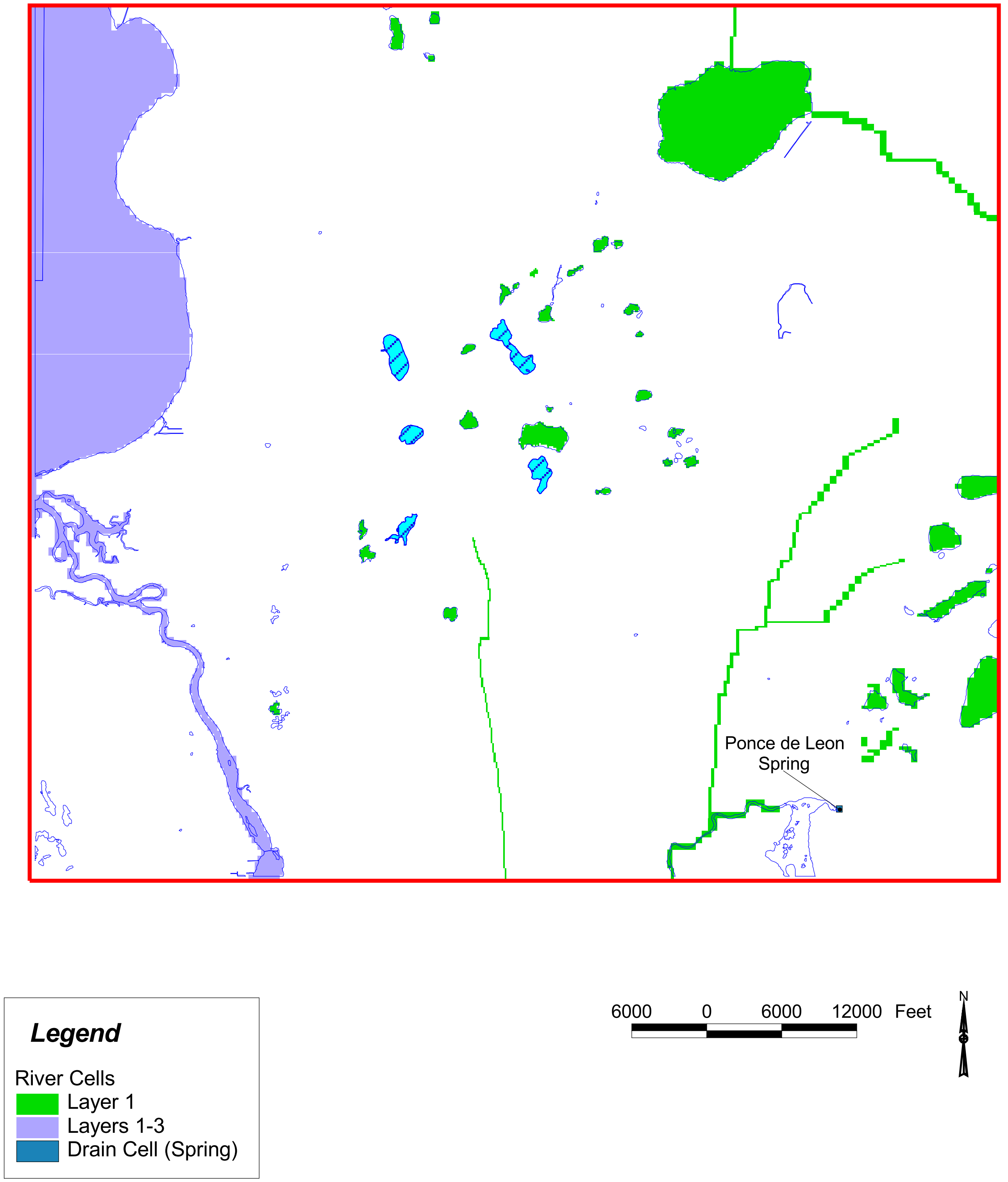

Figure 20. Secondary Lakes, Streams, and Springs

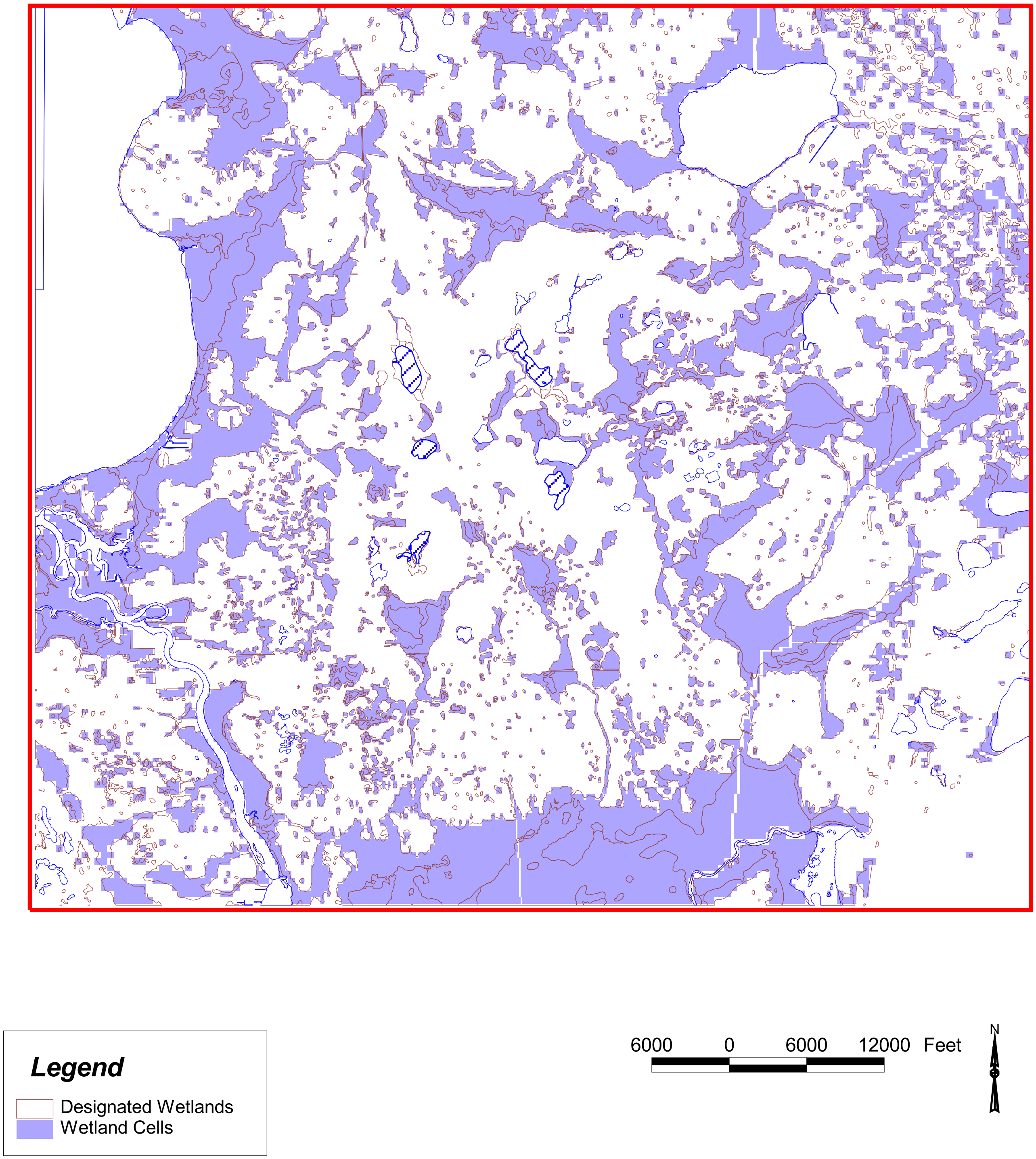

Figure 21. Modeled Wetlands

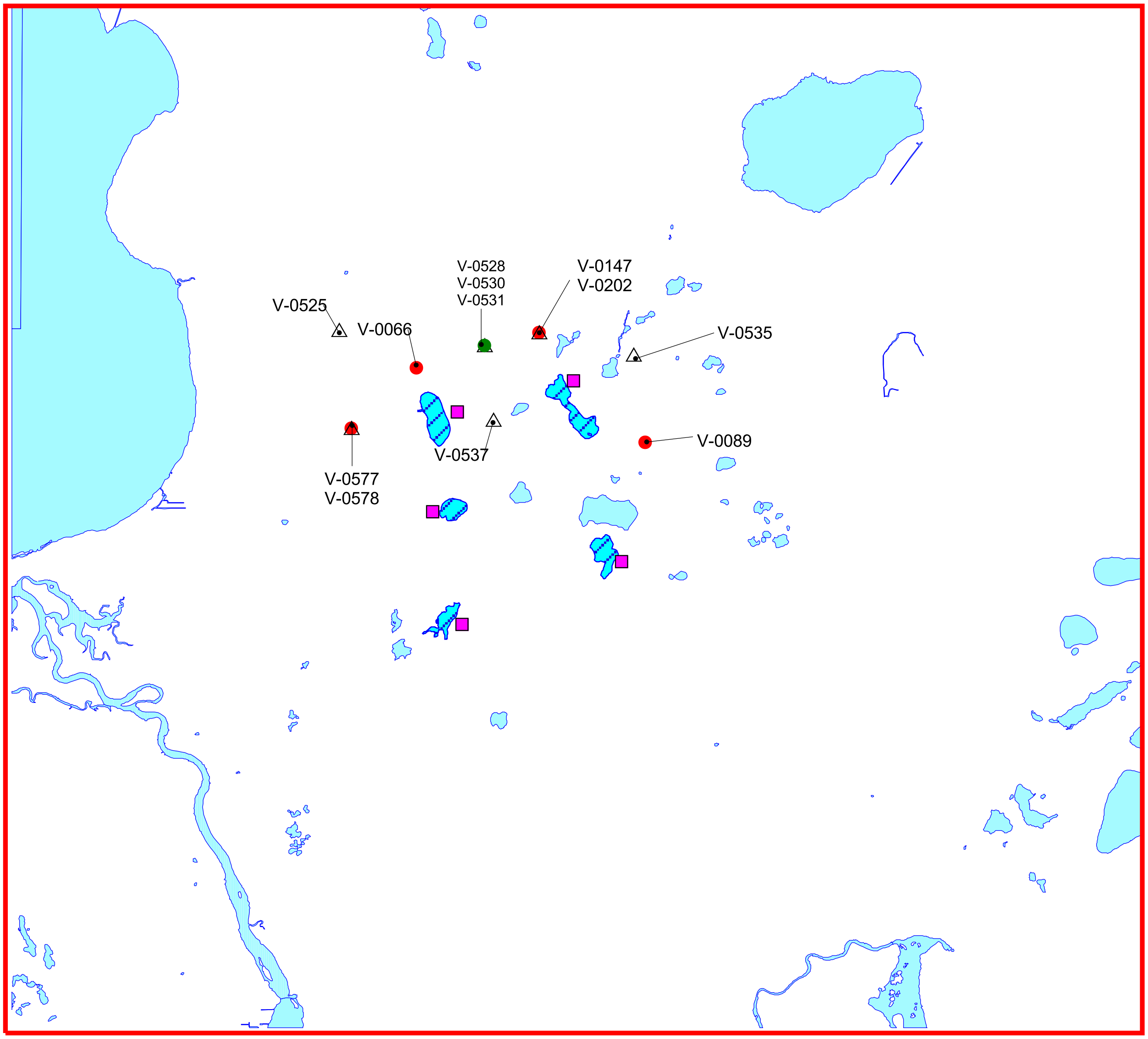

Figure 22. Observation Wells Used as Calibration Targets

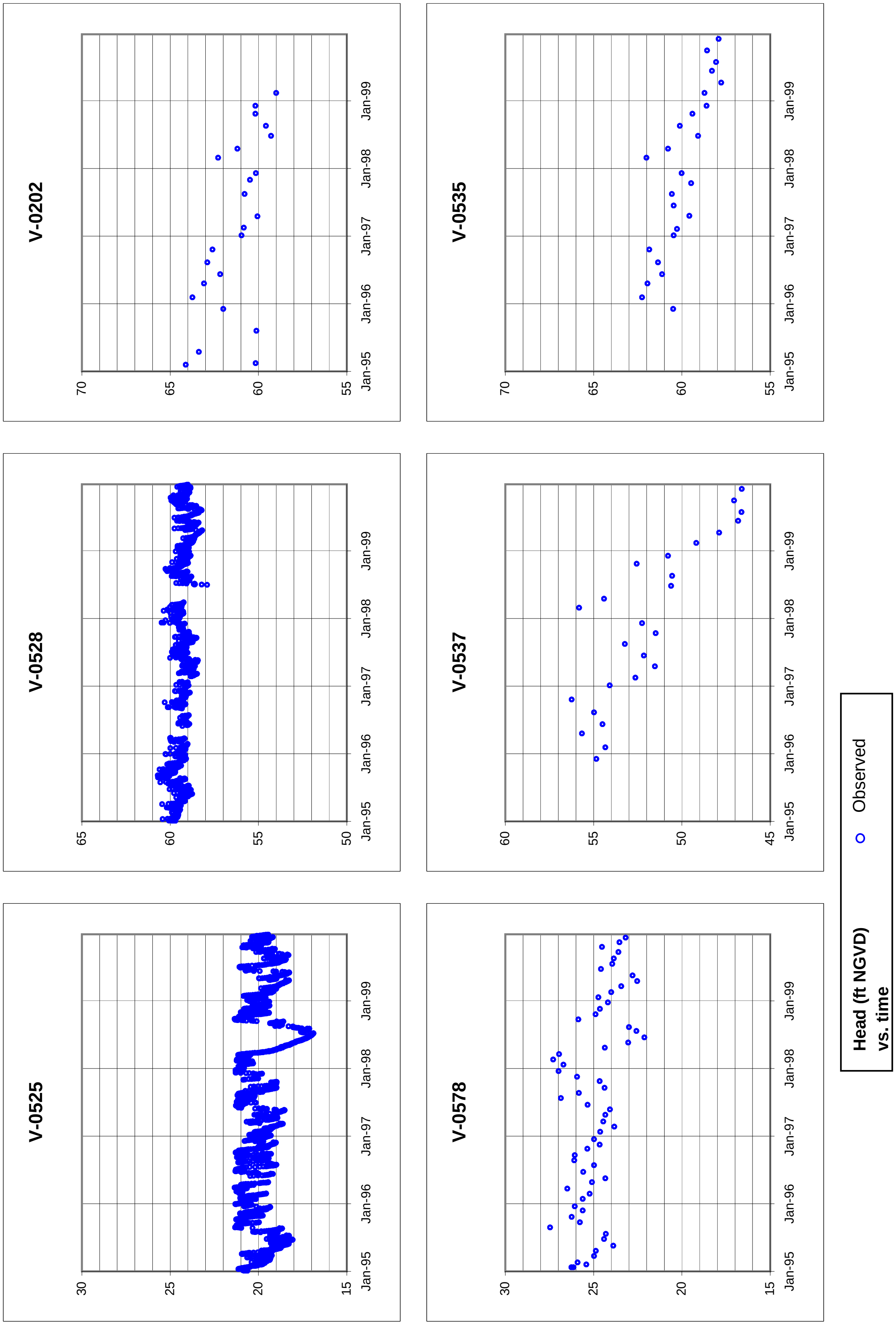

Figure 23. Observed Head at SAS Calibration Targets

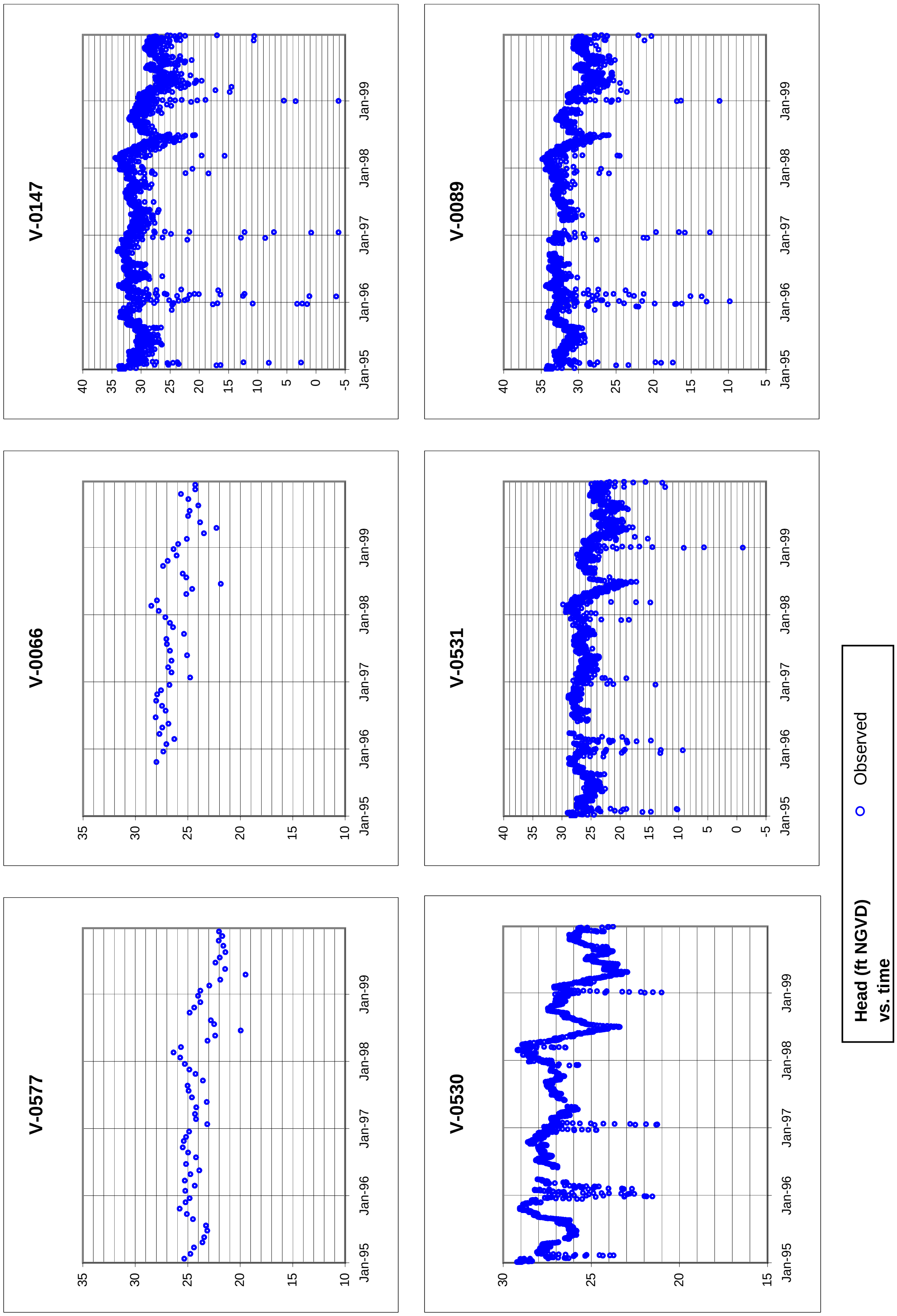

Figure 24. Observed Head at Floridan Aquifer Calibration Targets

Figure 25. Observed Stage at the Lakes of Interest

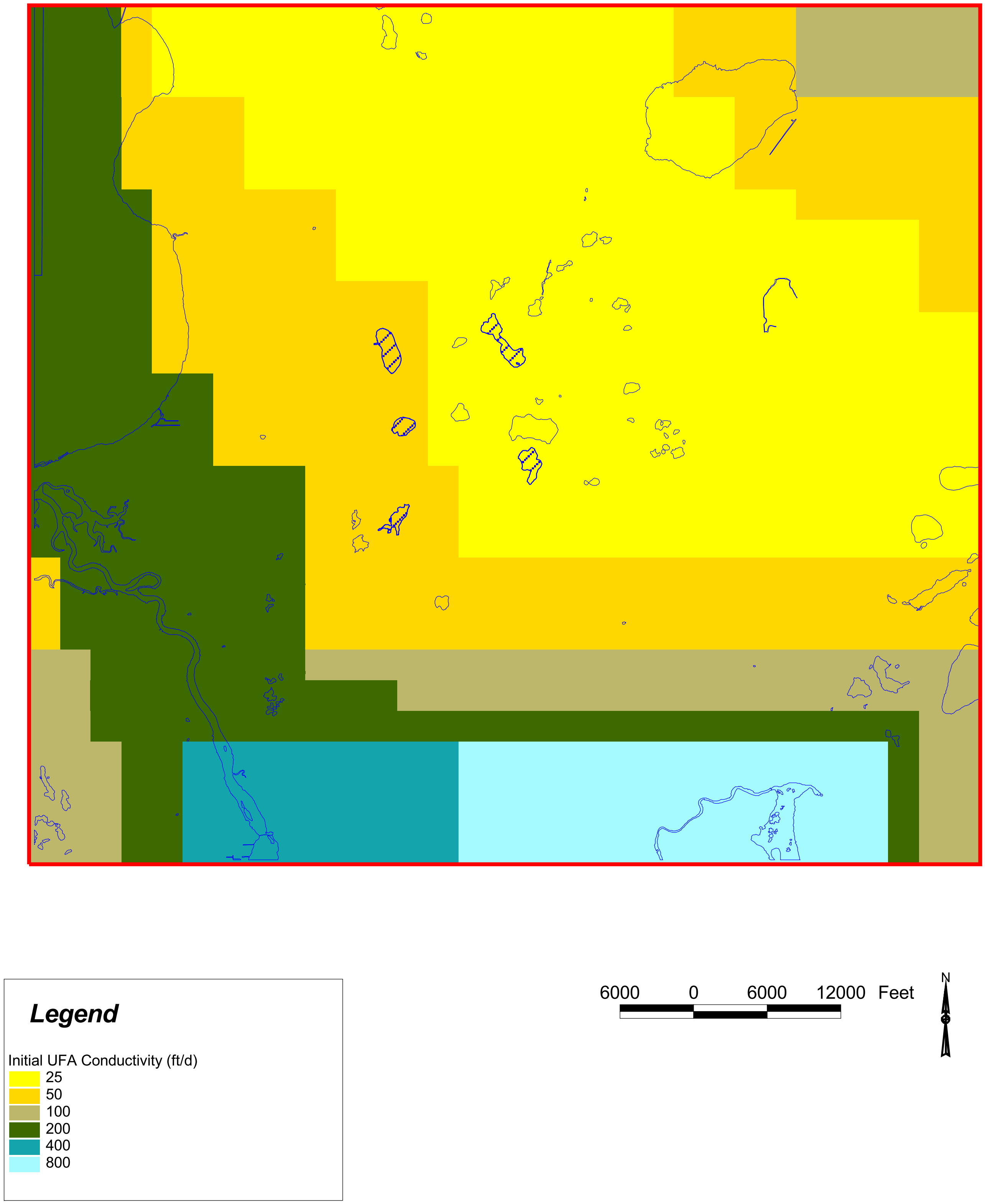

Figure 26. UFA Conductivity Zones

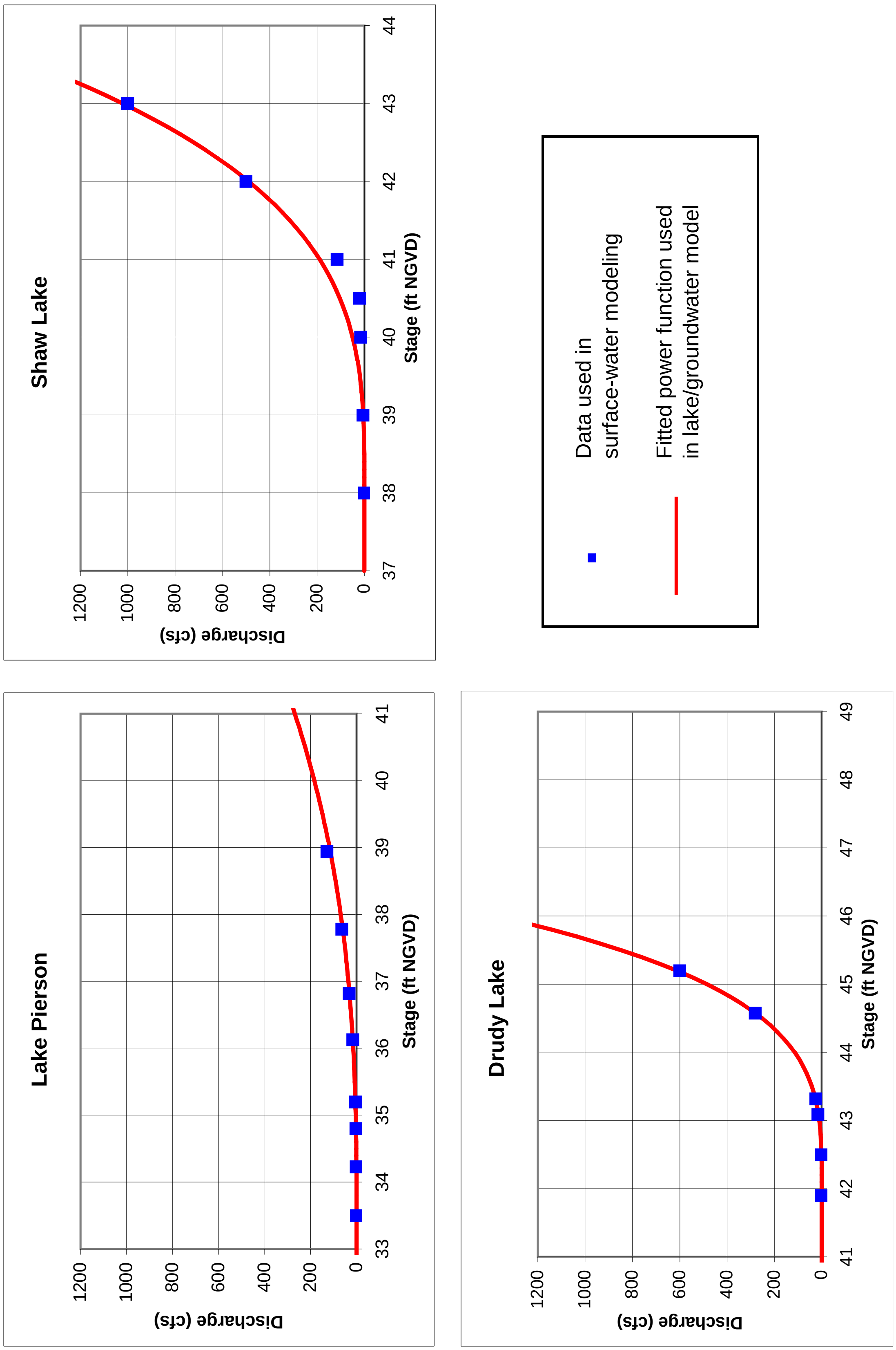

Figure 27. Initial Specification of Lake Stage-Discharge Functions

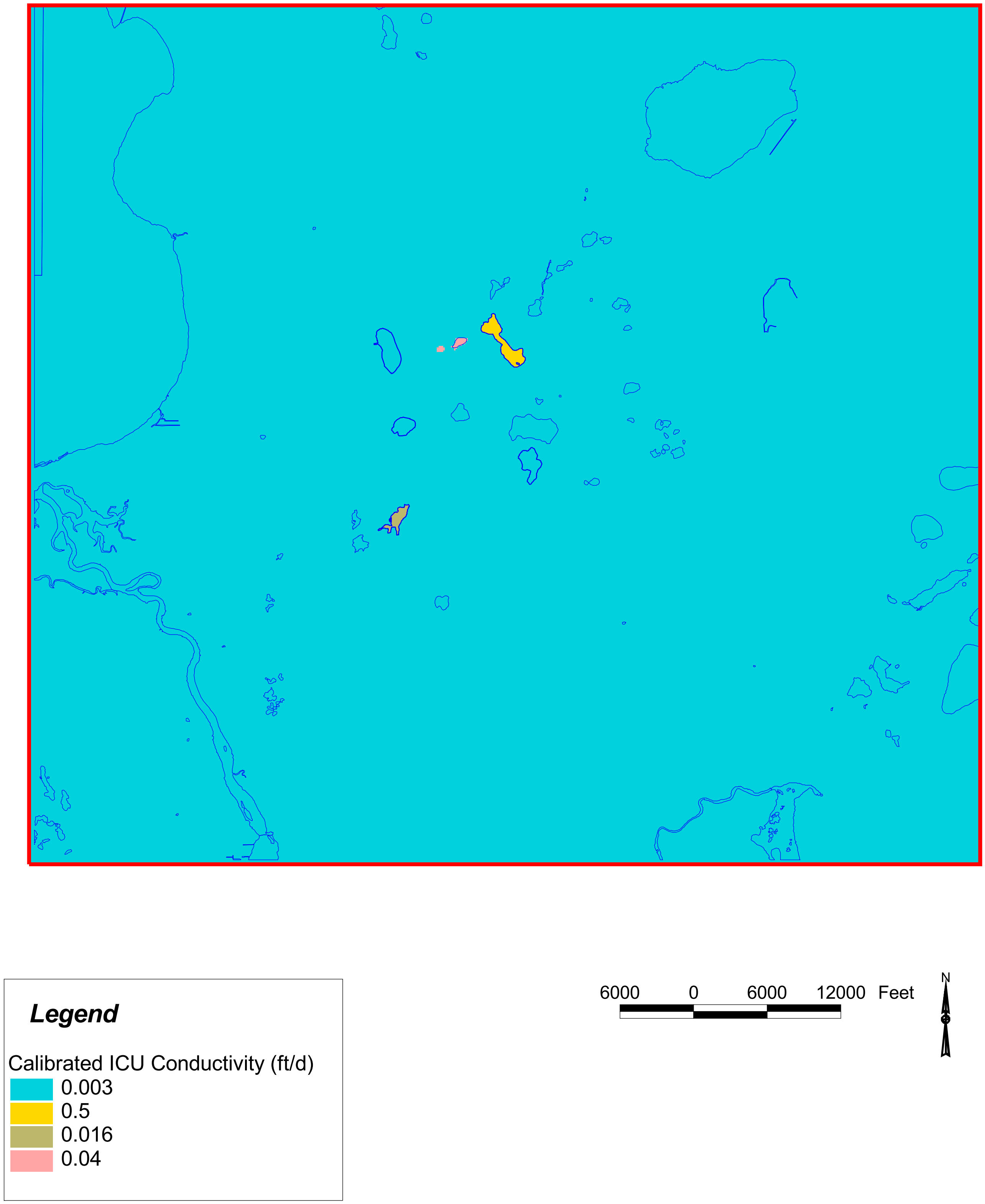

Figure 28. ICU Conductivity Zones

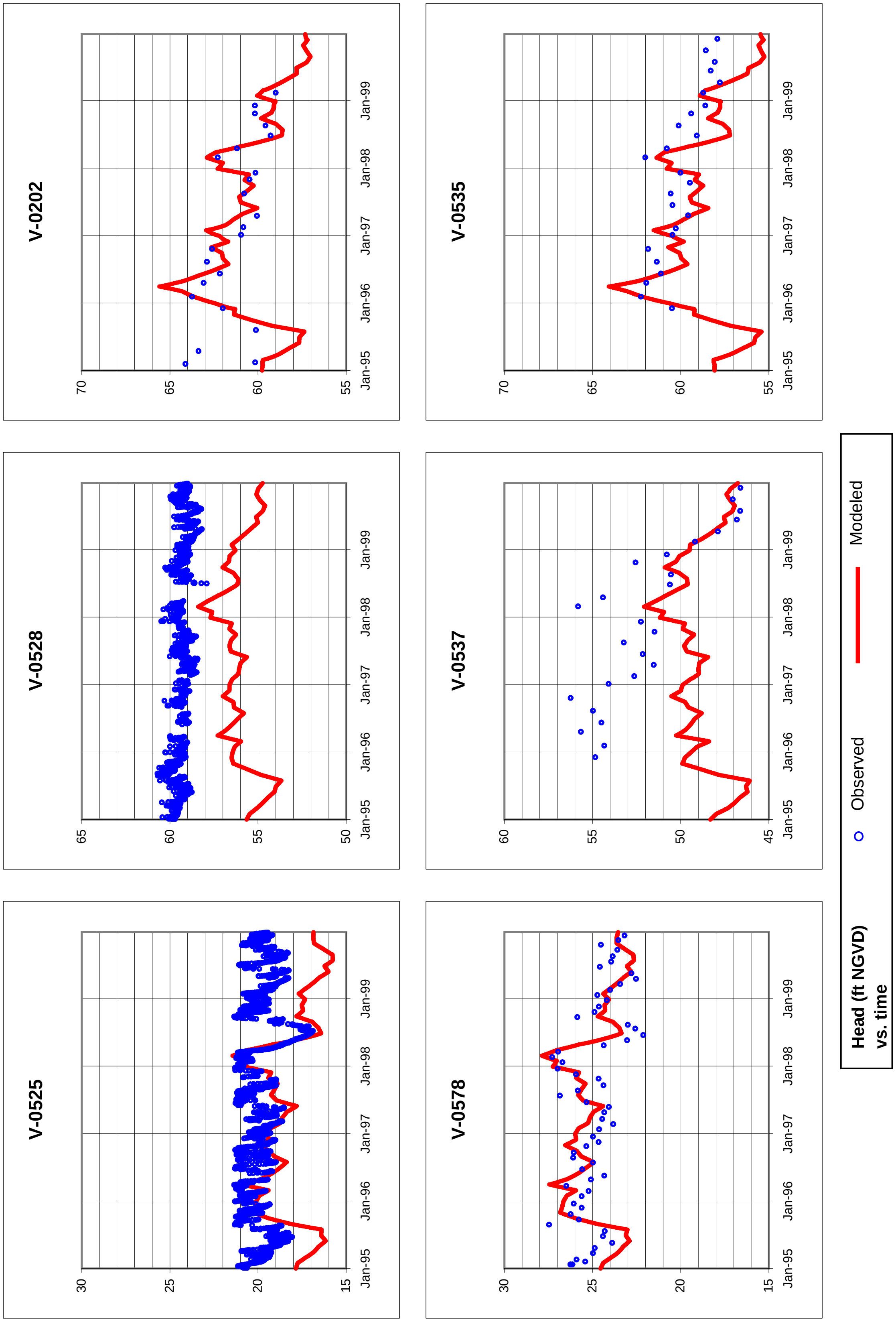

Figure 29. Calibration to SAS Observation Wells

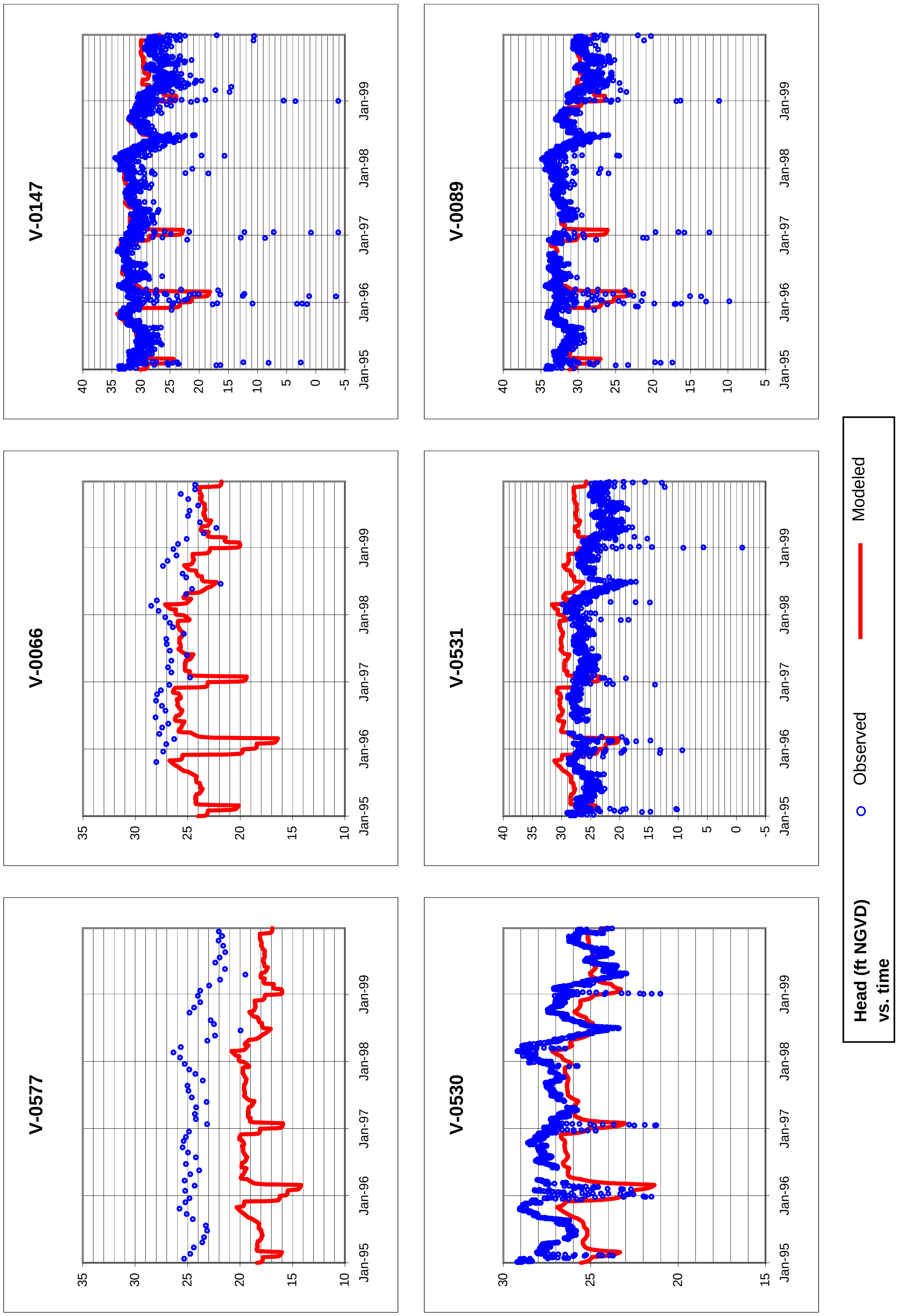

Figure 30. Calibration to Floridan Aquifer Observation Wells

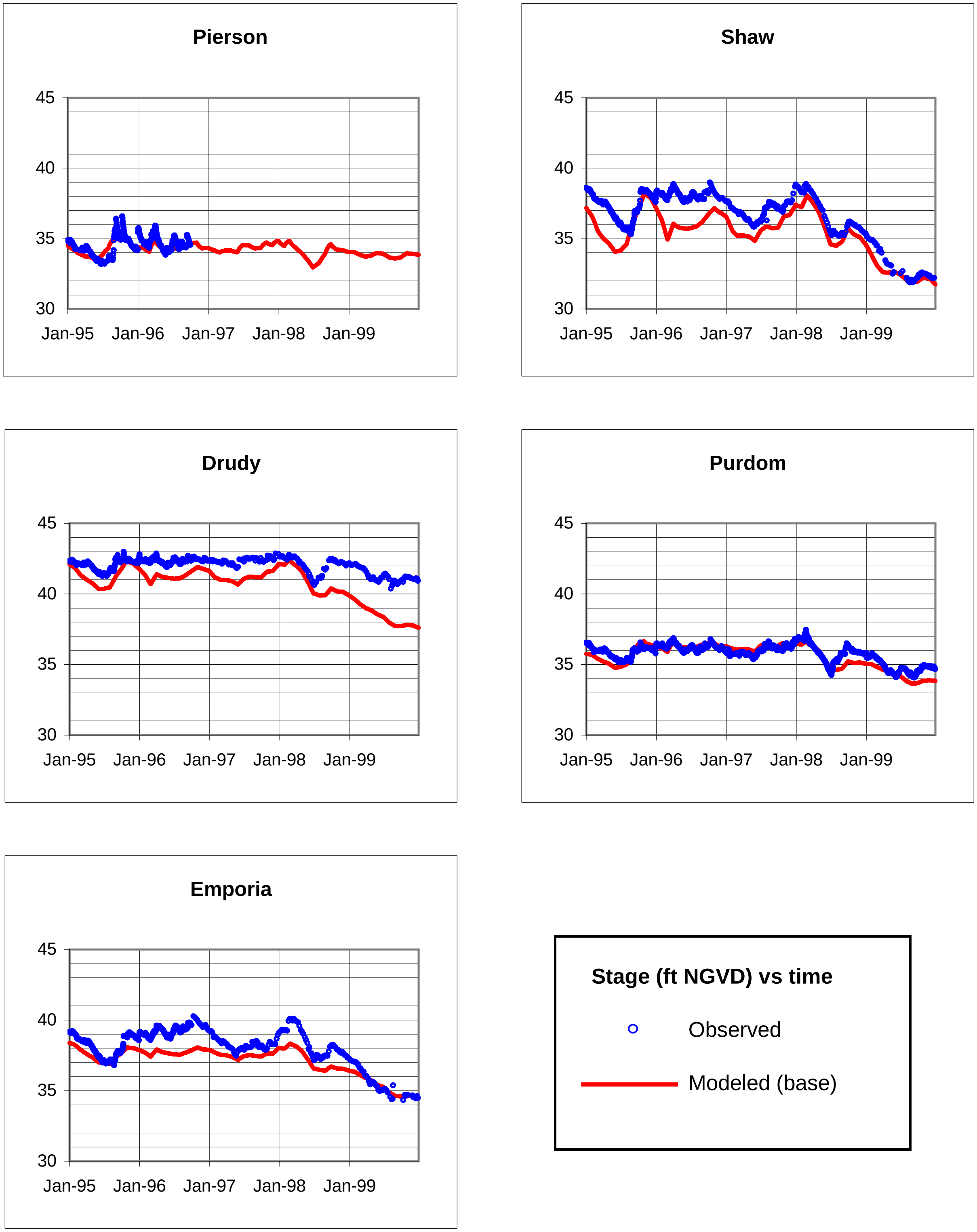

Figure 31. Calibration to Lake Levels

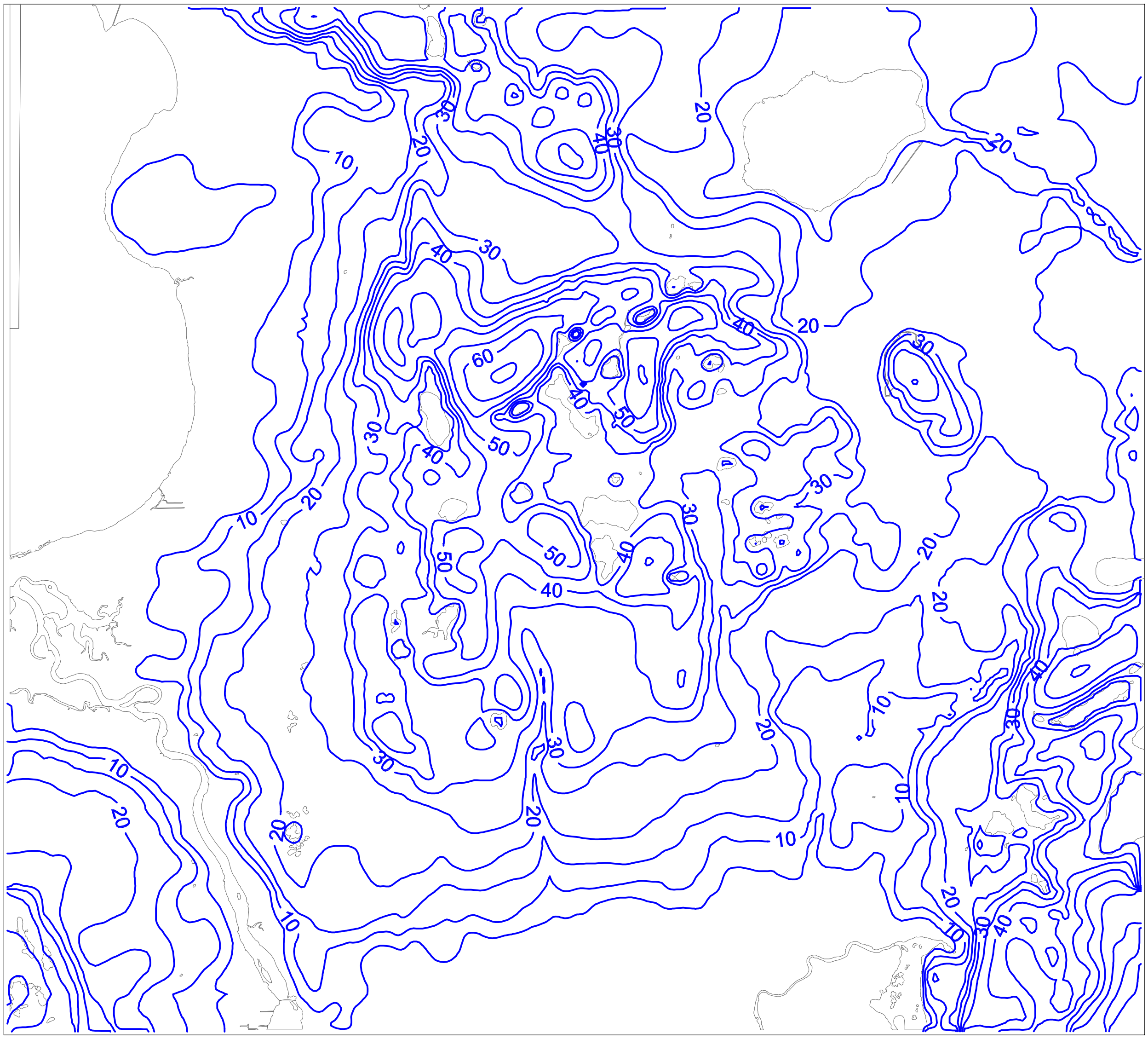

Figure 32. Modeled Steady-State Head in the SAS

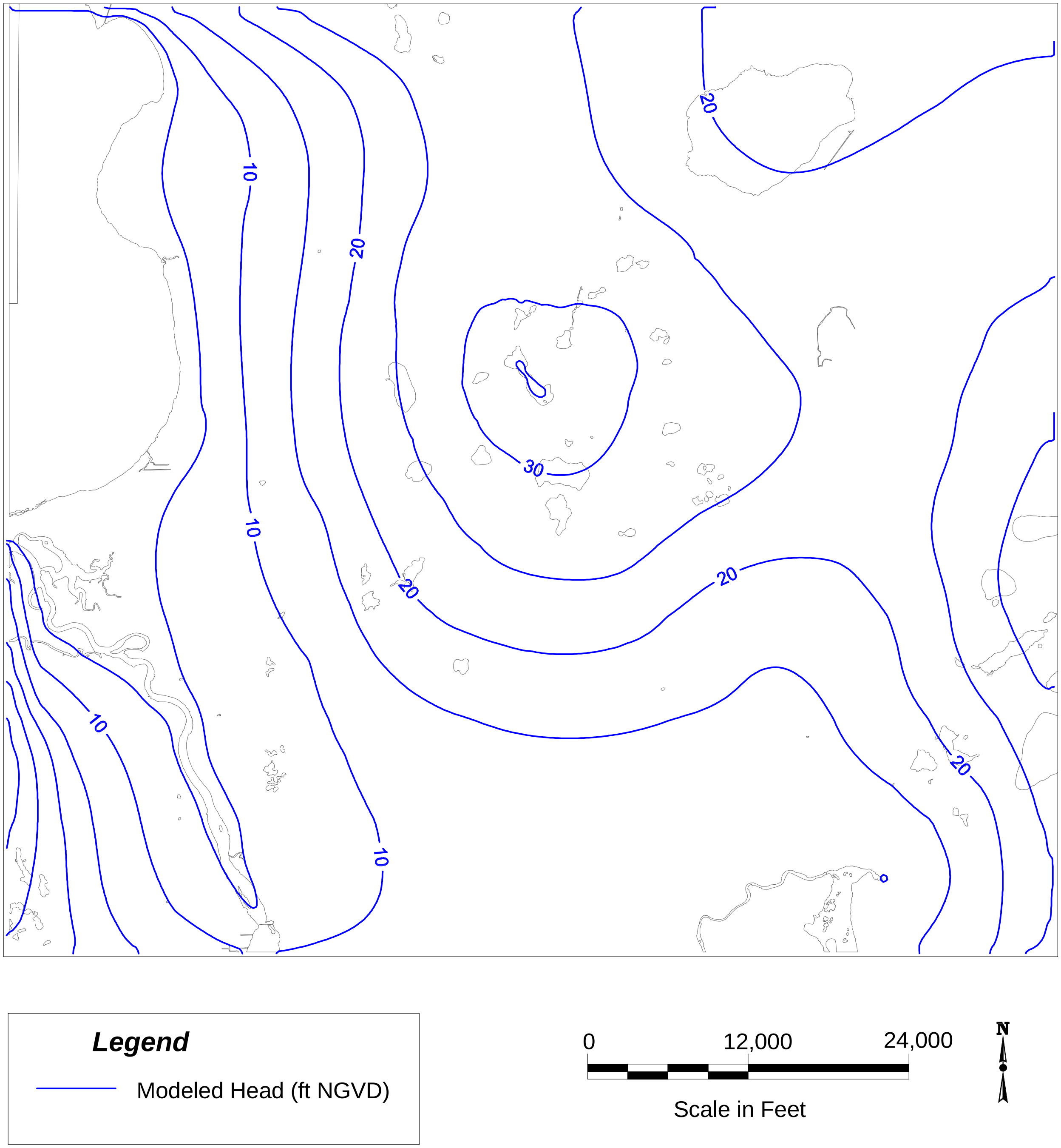

Figure 33. Modeled Steady-State Head in the UFA

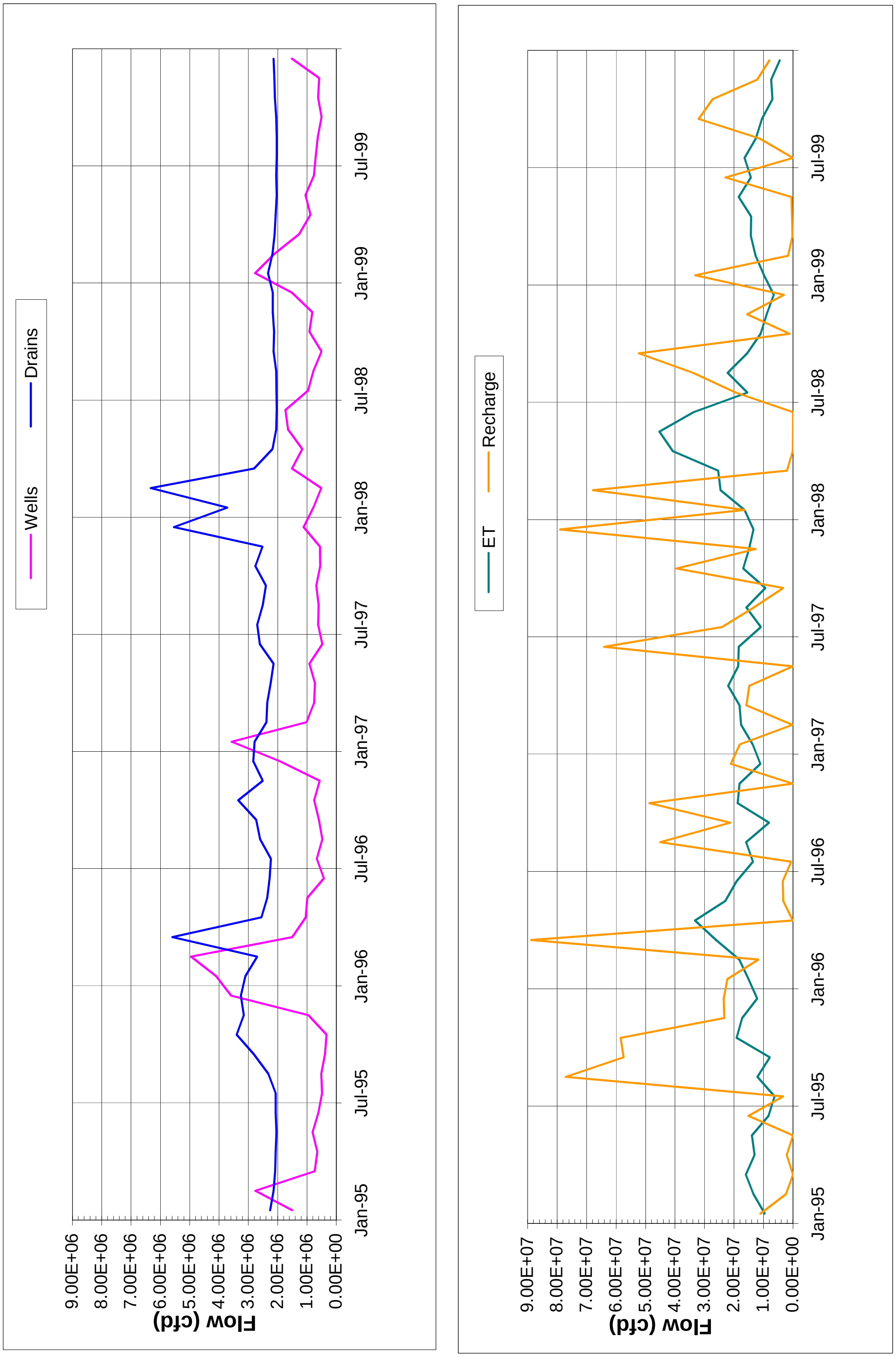

Figure 34. Groundwater Inflows and Outflows

Figure 35. Lake Inflows and Outflows

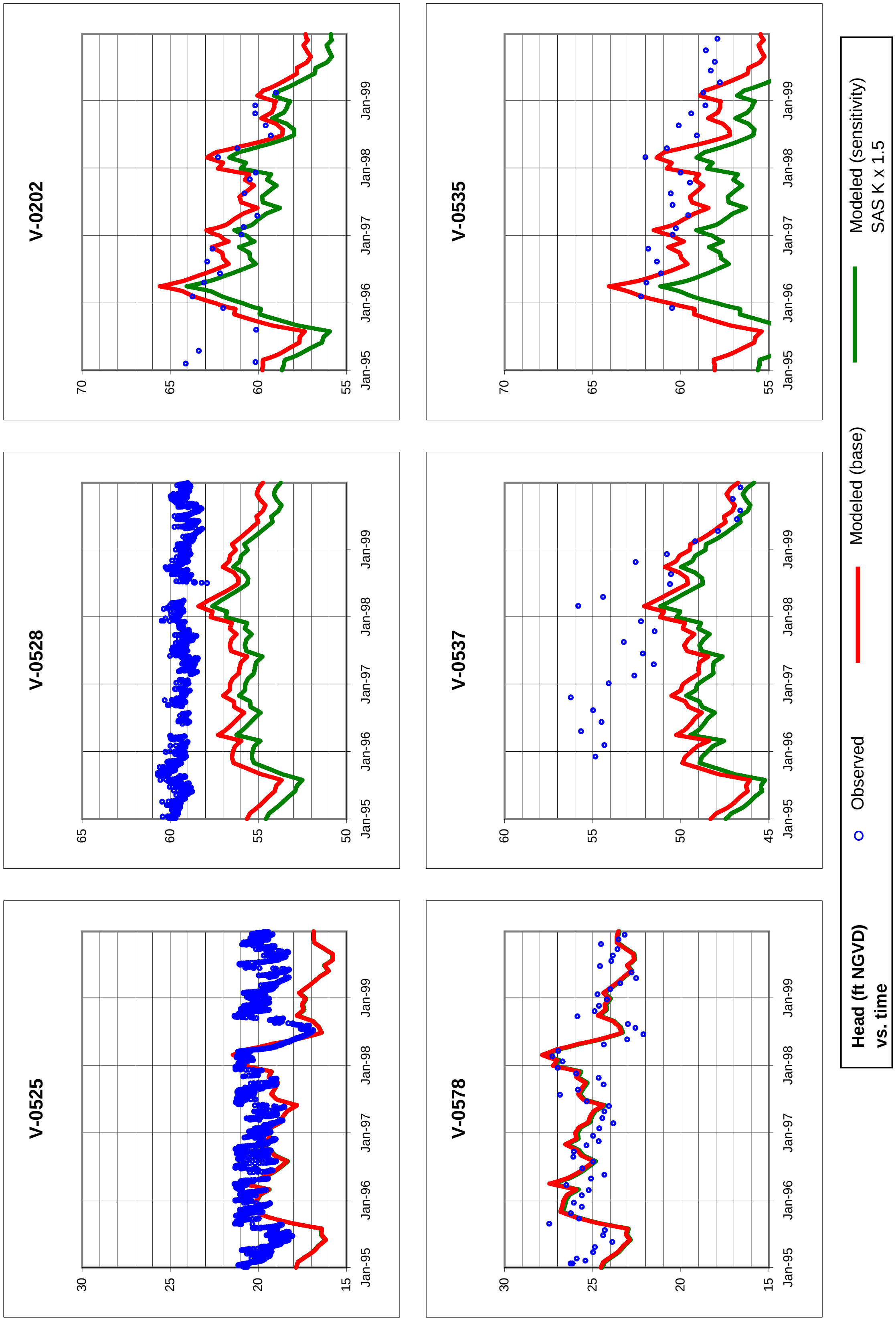

Figure 36. Sensitivity of SAS Wells to Increased SAS Hydraulic Conductivity

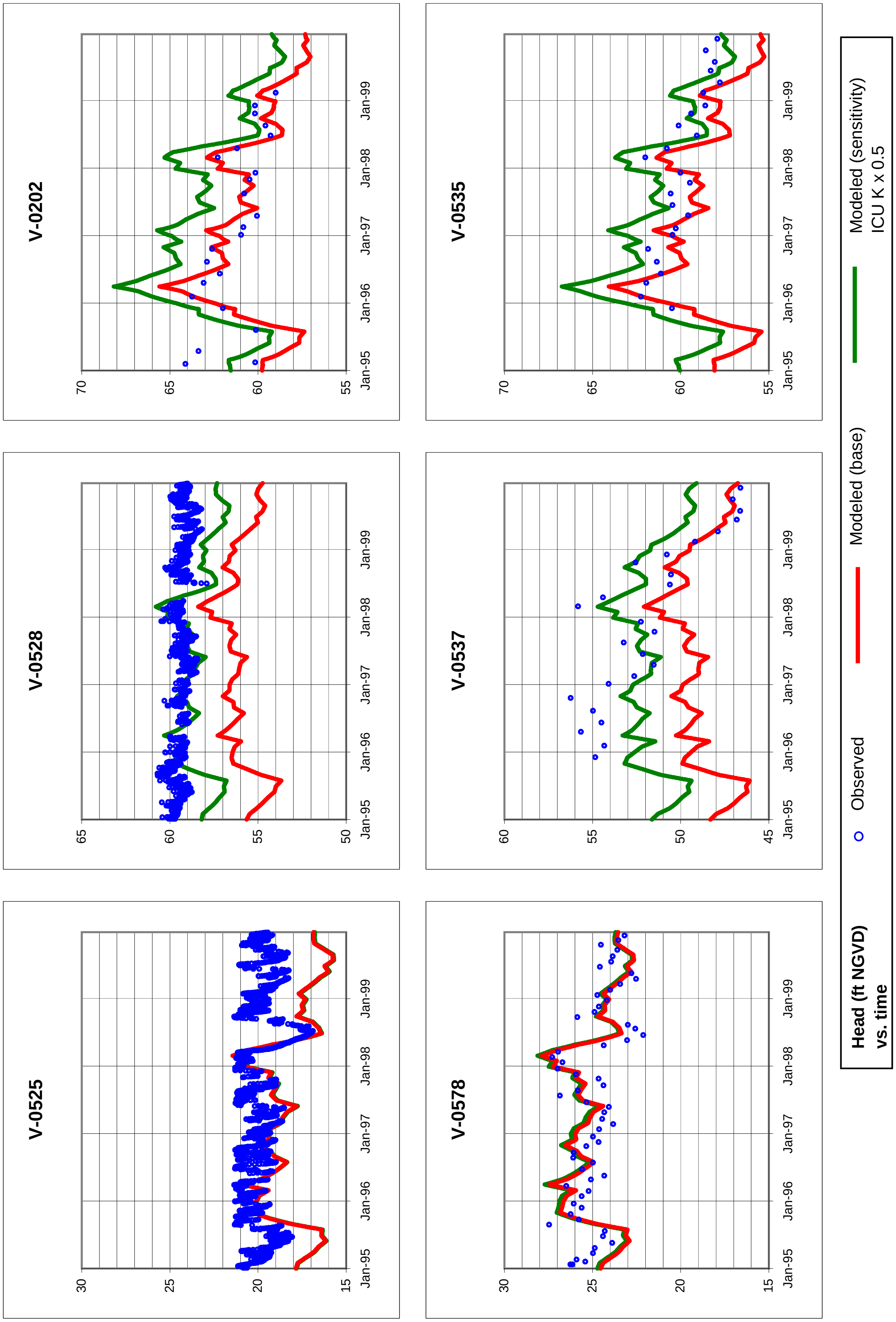

Figure 37. Sensitivity of SAS Wells to Decreased ICU Hydraulic Conductivity

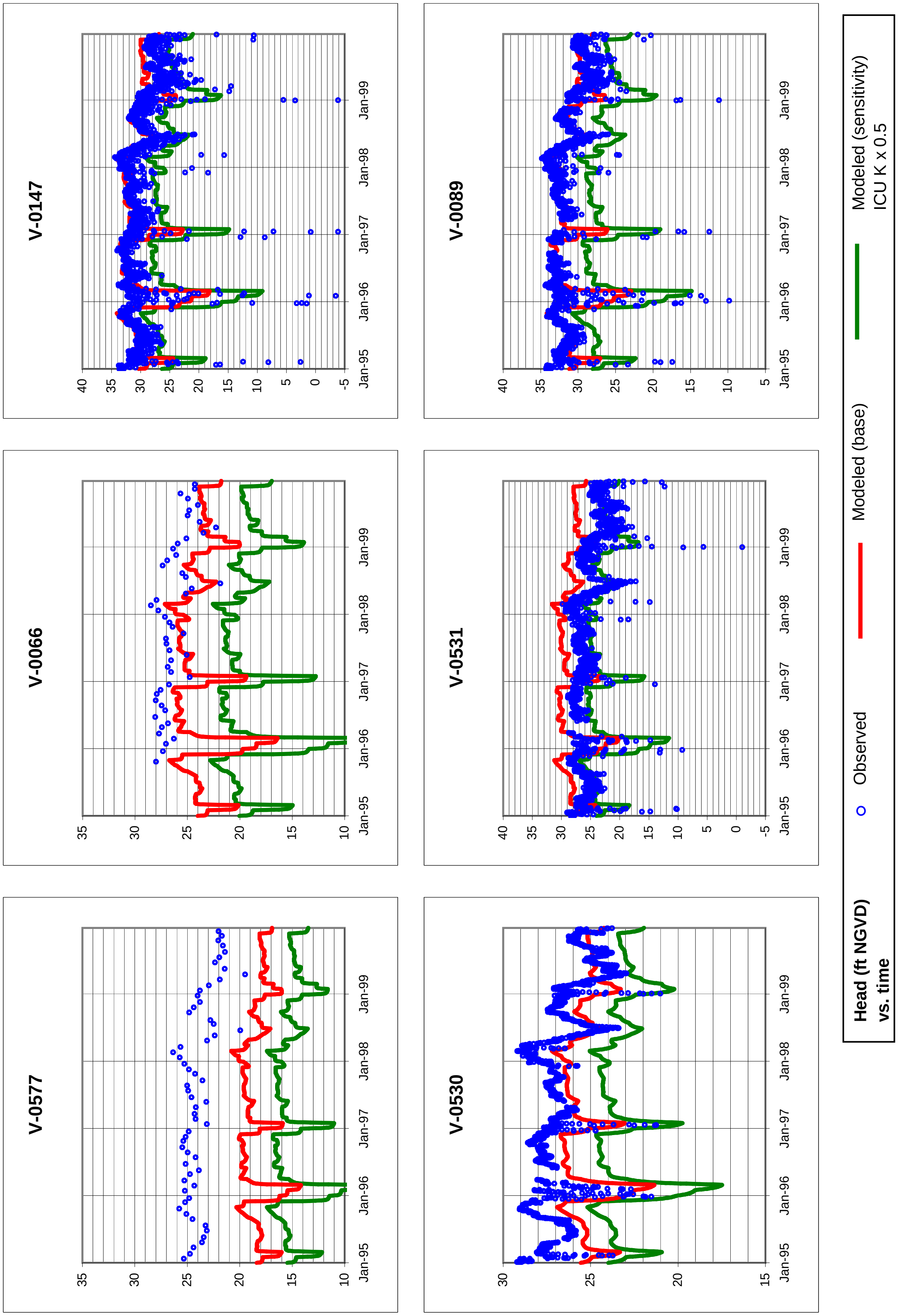

Figure 38. Sensitivity of Floridan Wells to Decreased ICU Hydraulic Conductivity

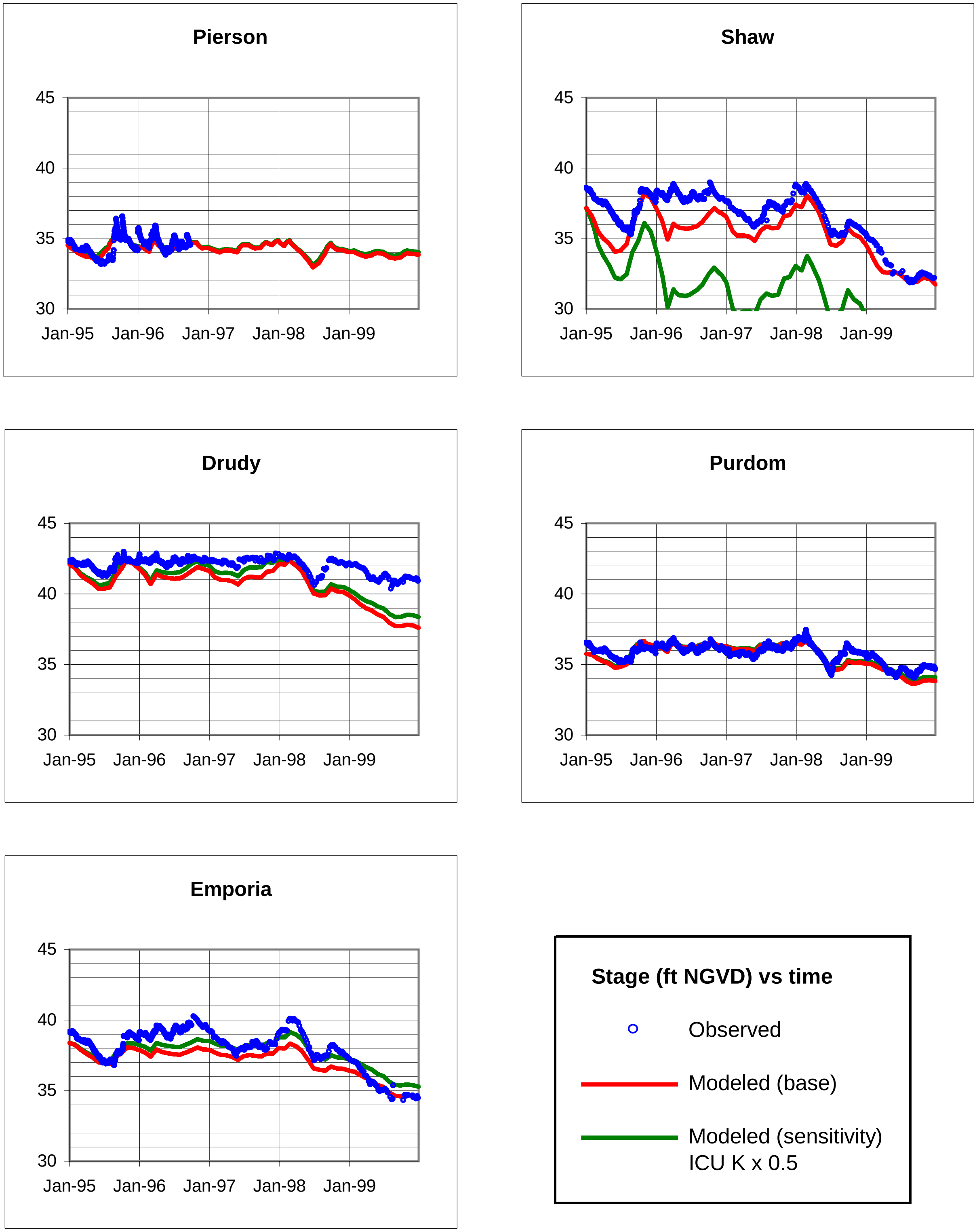

Figure 39. Sensitivity of Lake Levels to Decreased ICU Hydraulic Conductivity

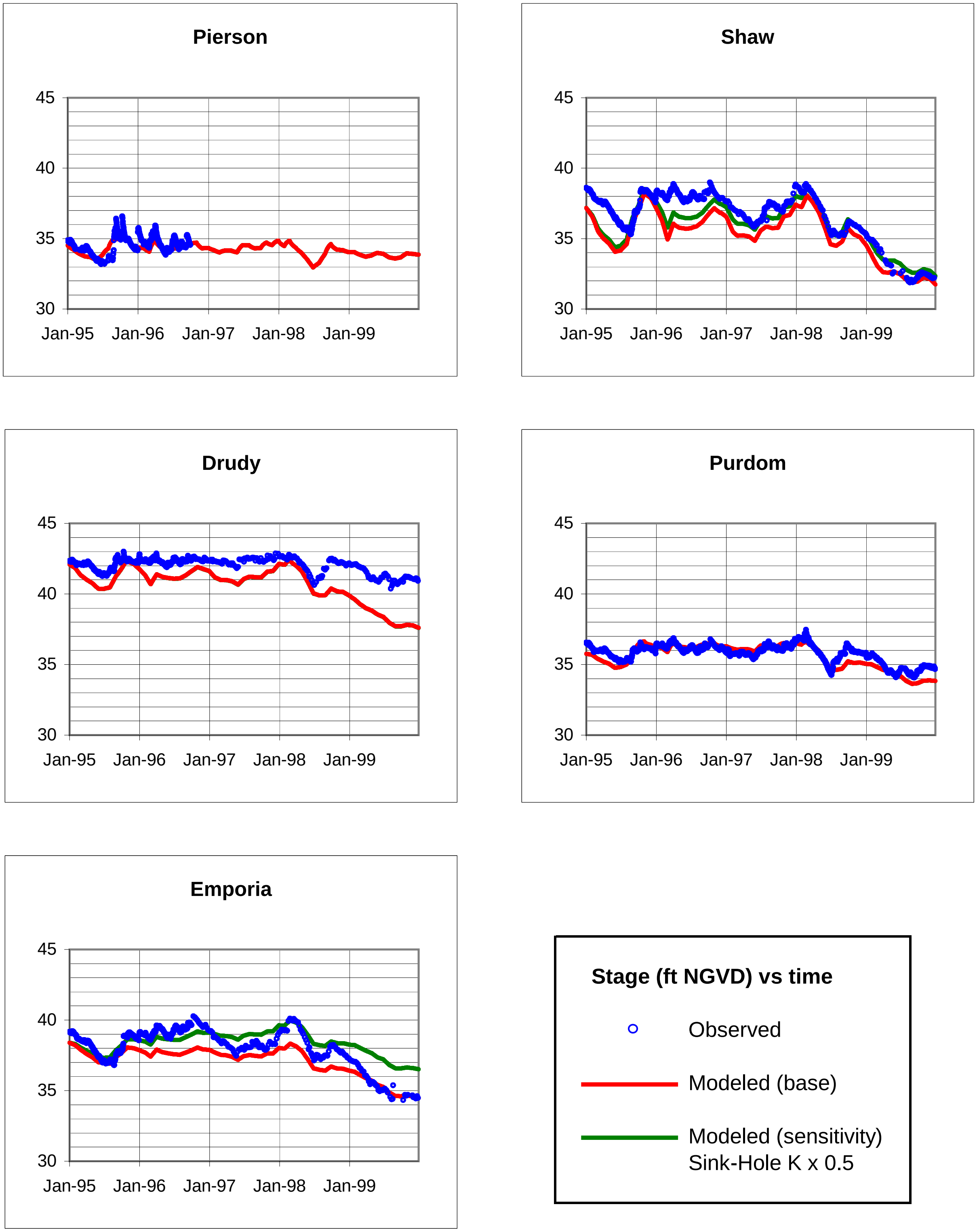

Figure 40. Sensitivity of Lake Levels to Decreased ICU Sink-Hole Conductivity

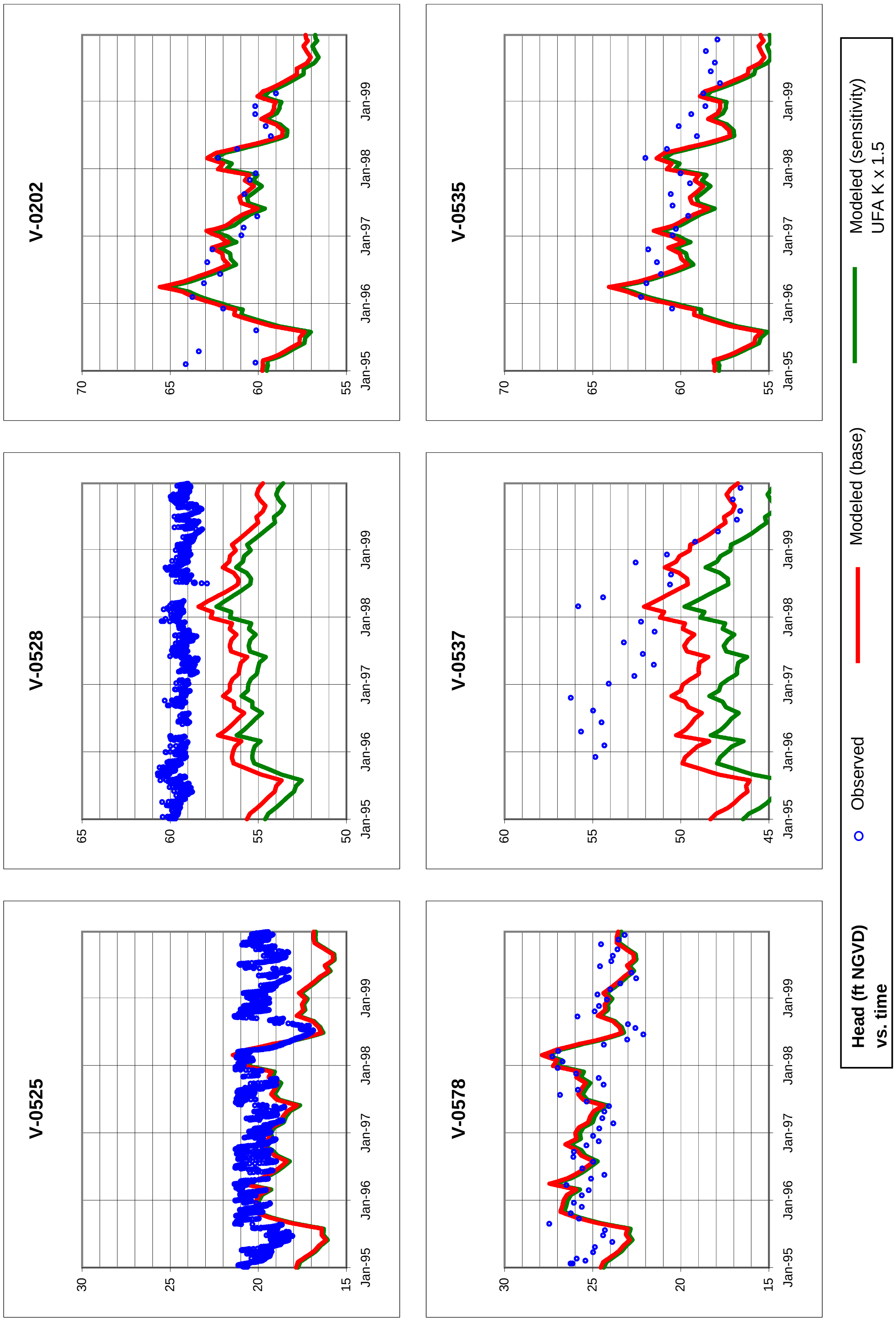

Figure 41. Sensitivity of SAS Wells to Increased UFA Hydraulic Conductivity

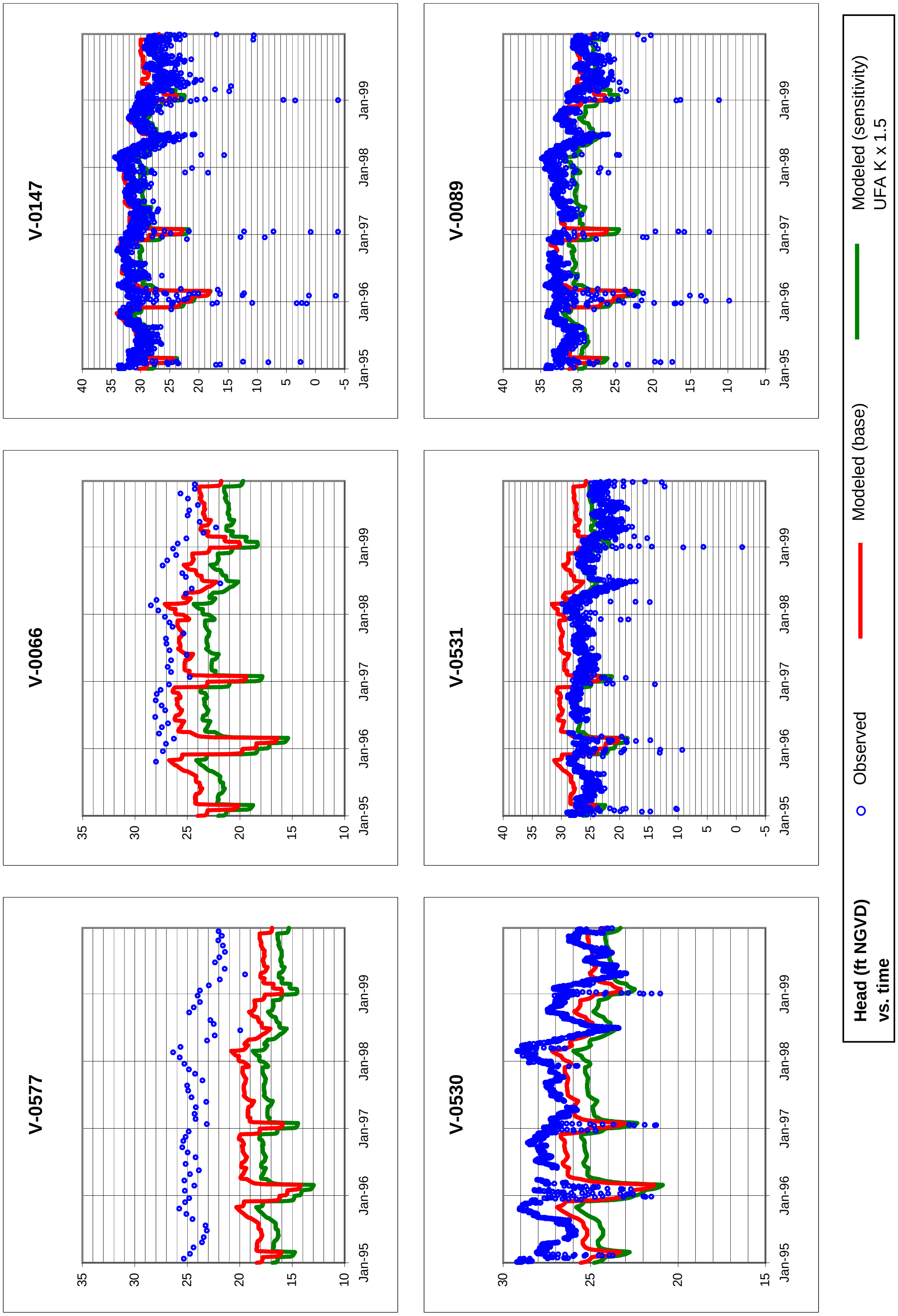

Figure 42. Sensitivity of Floridan Wells to Increased UFA Hydraulic Conductivity

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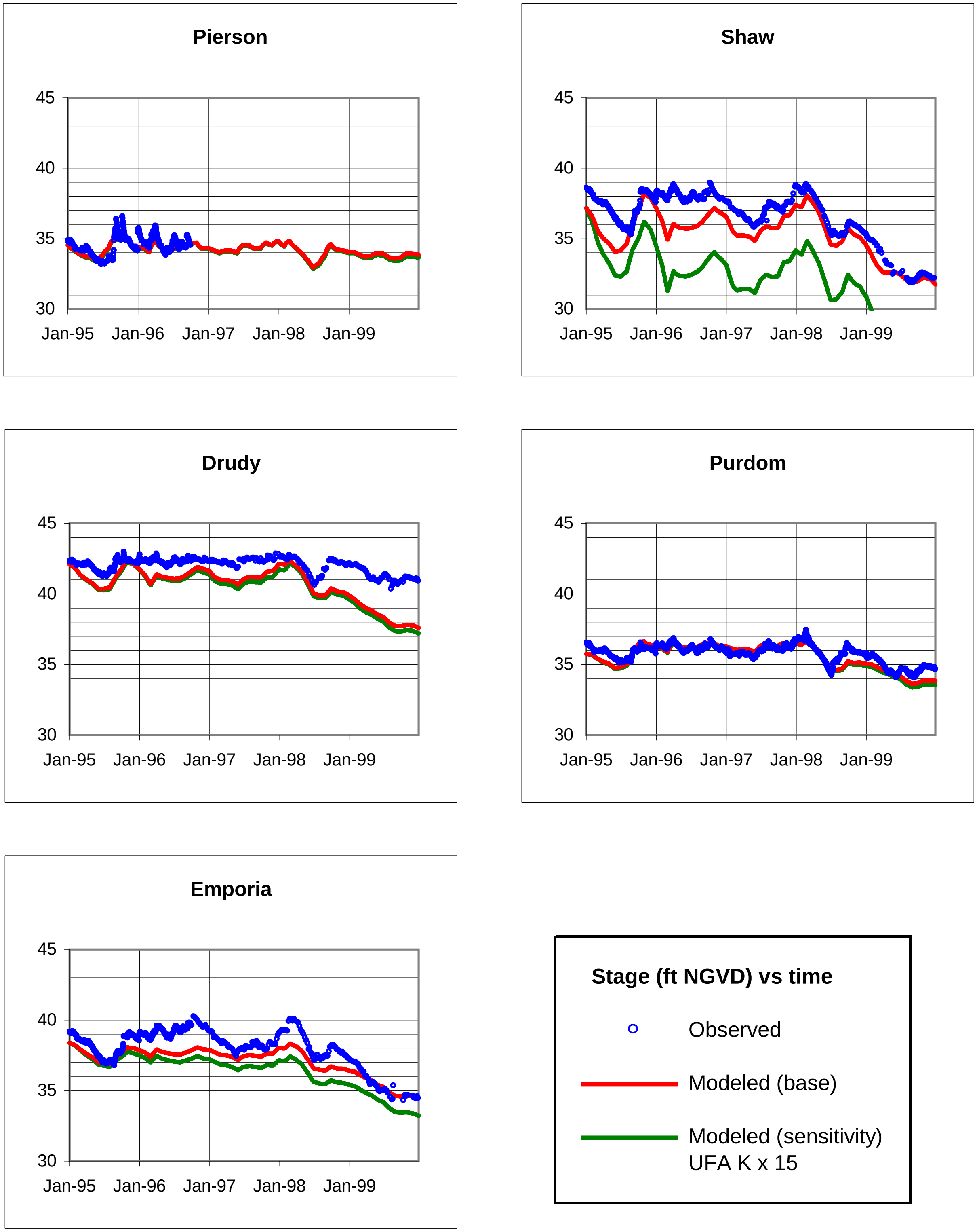

Figure 43. Sensitivity of Lake Levels to Increased UFA Hydraulic Conductivity

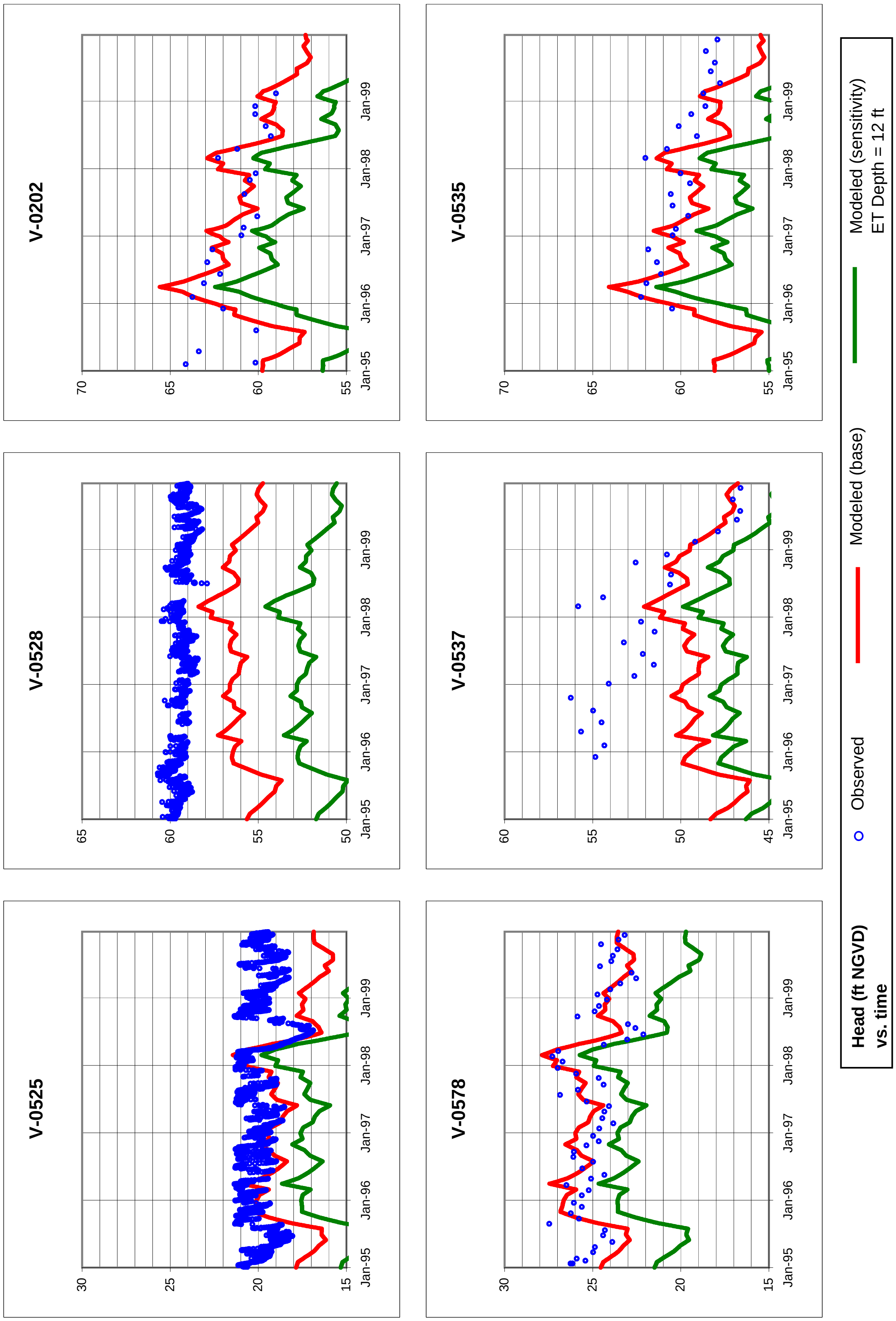

Figure 44. Sensitivity of SAS Wells to Increased ET Extinction Depth

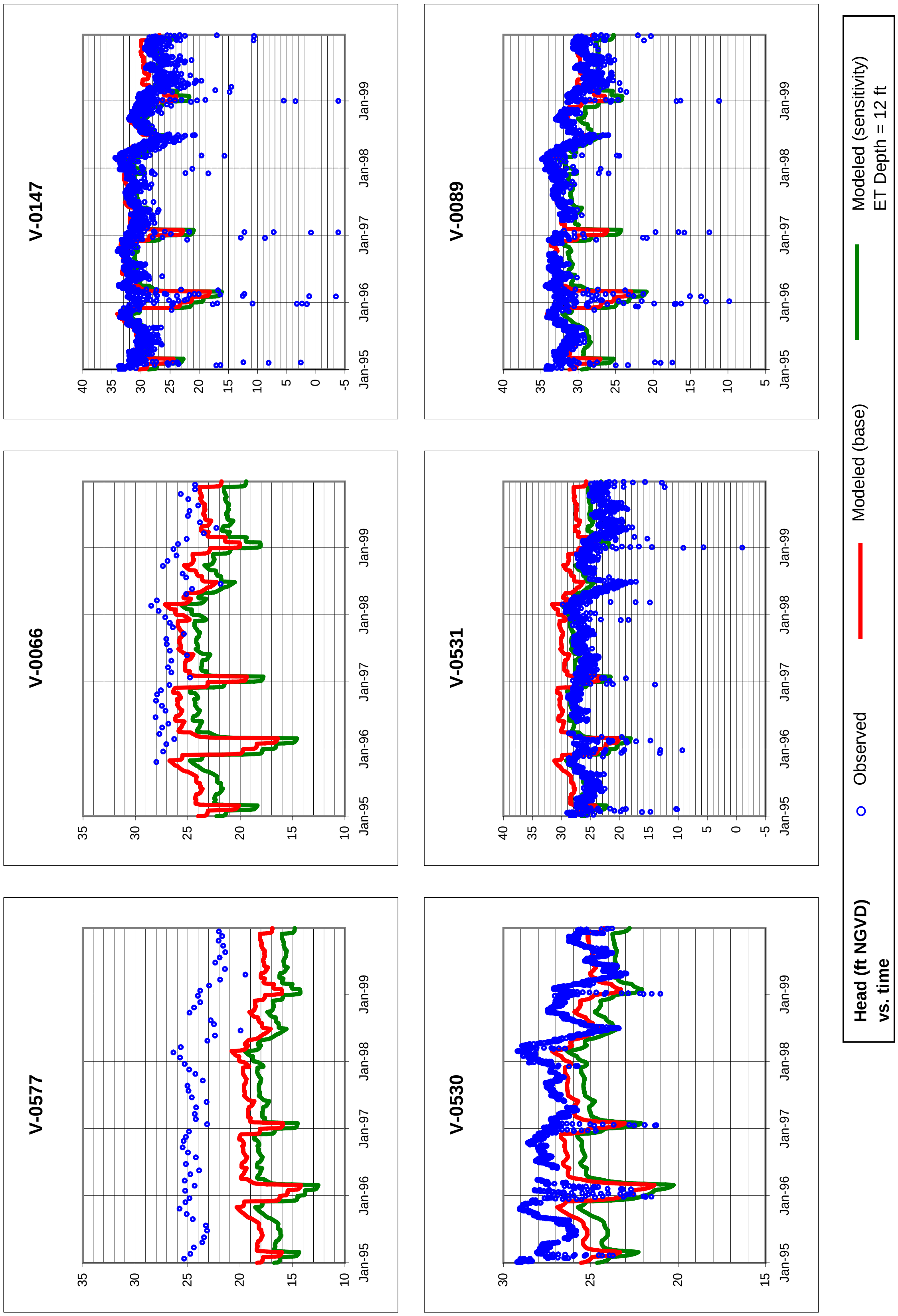

Figure 45. Sensitivity of Floridan Wells to Increased ET Extinction Depth

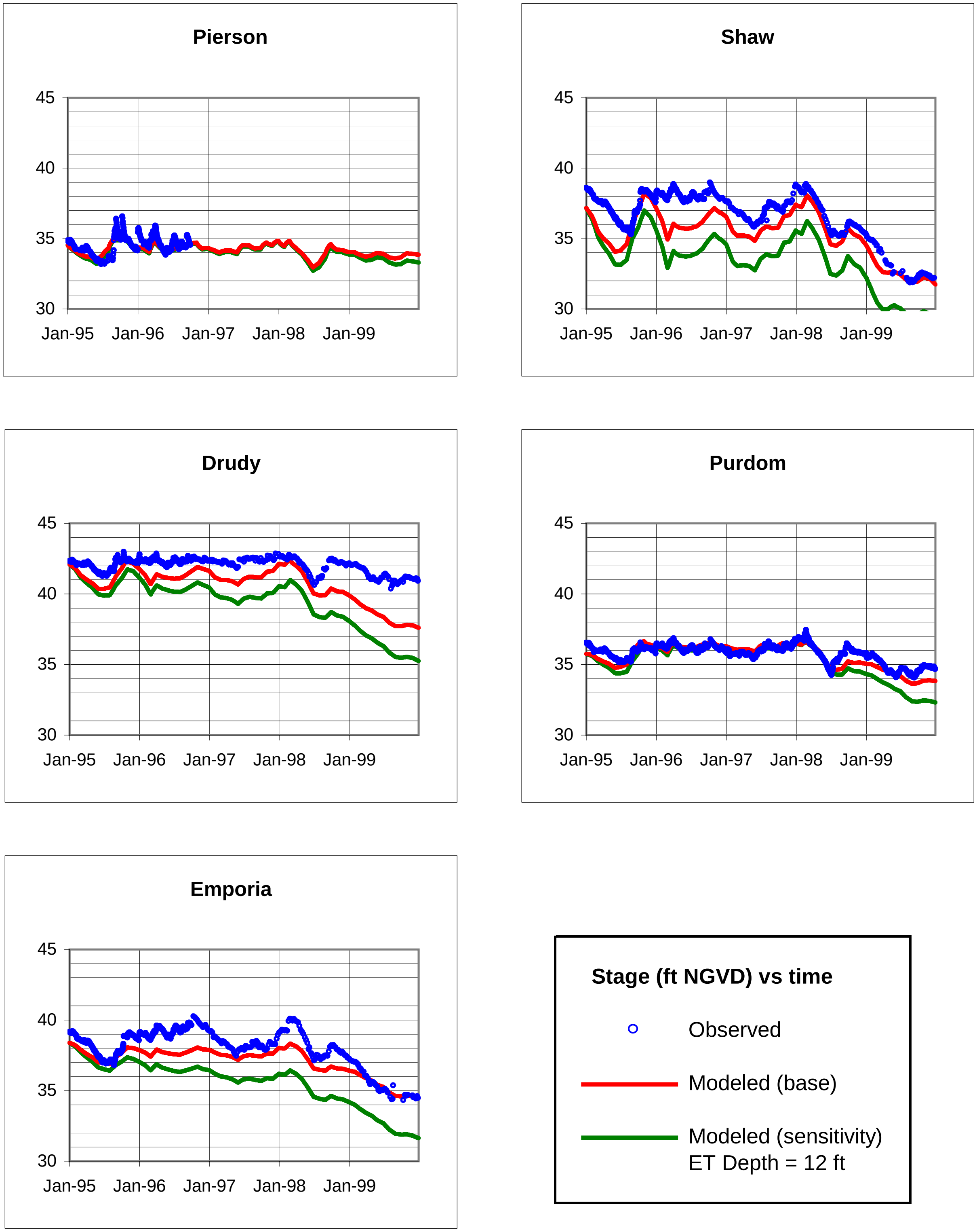

Figure 46. Sensitivity of Lake Levels to Increased ET Extinction Depth

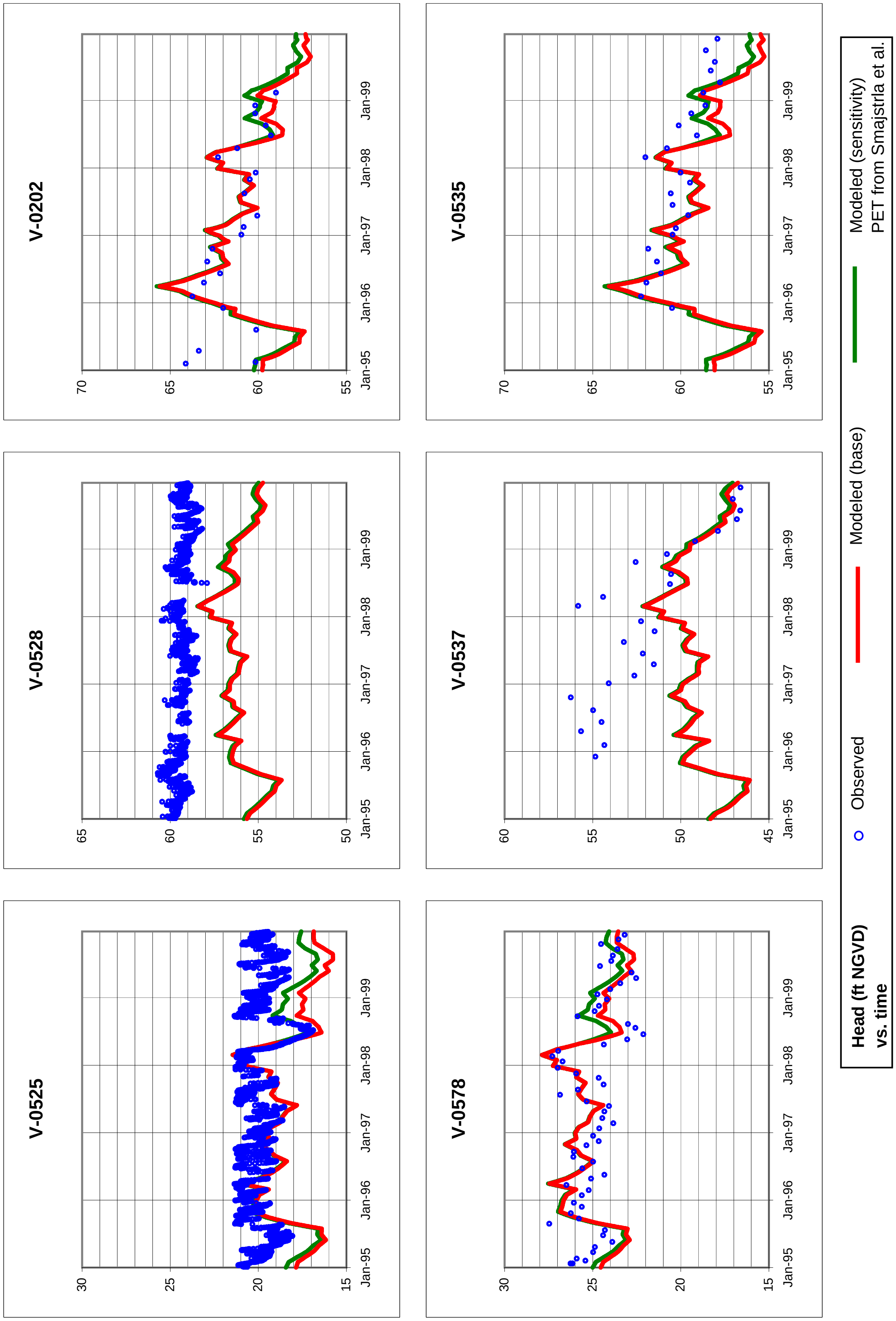

Figure 47. Sensitivity of SAS Wells to Reduced PET

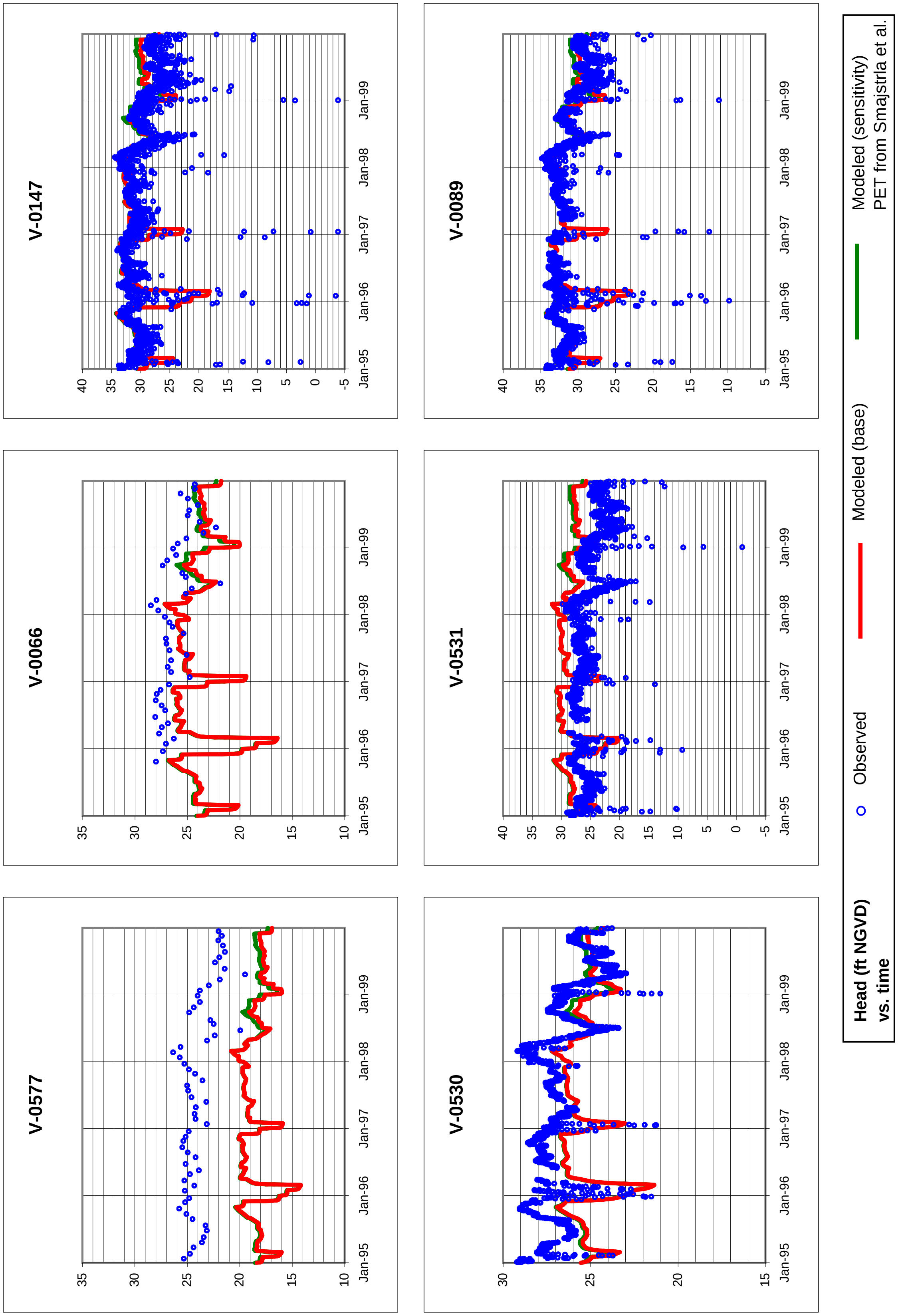

Figure 48. Sensitivity of Floridan Wells to Reduced PET

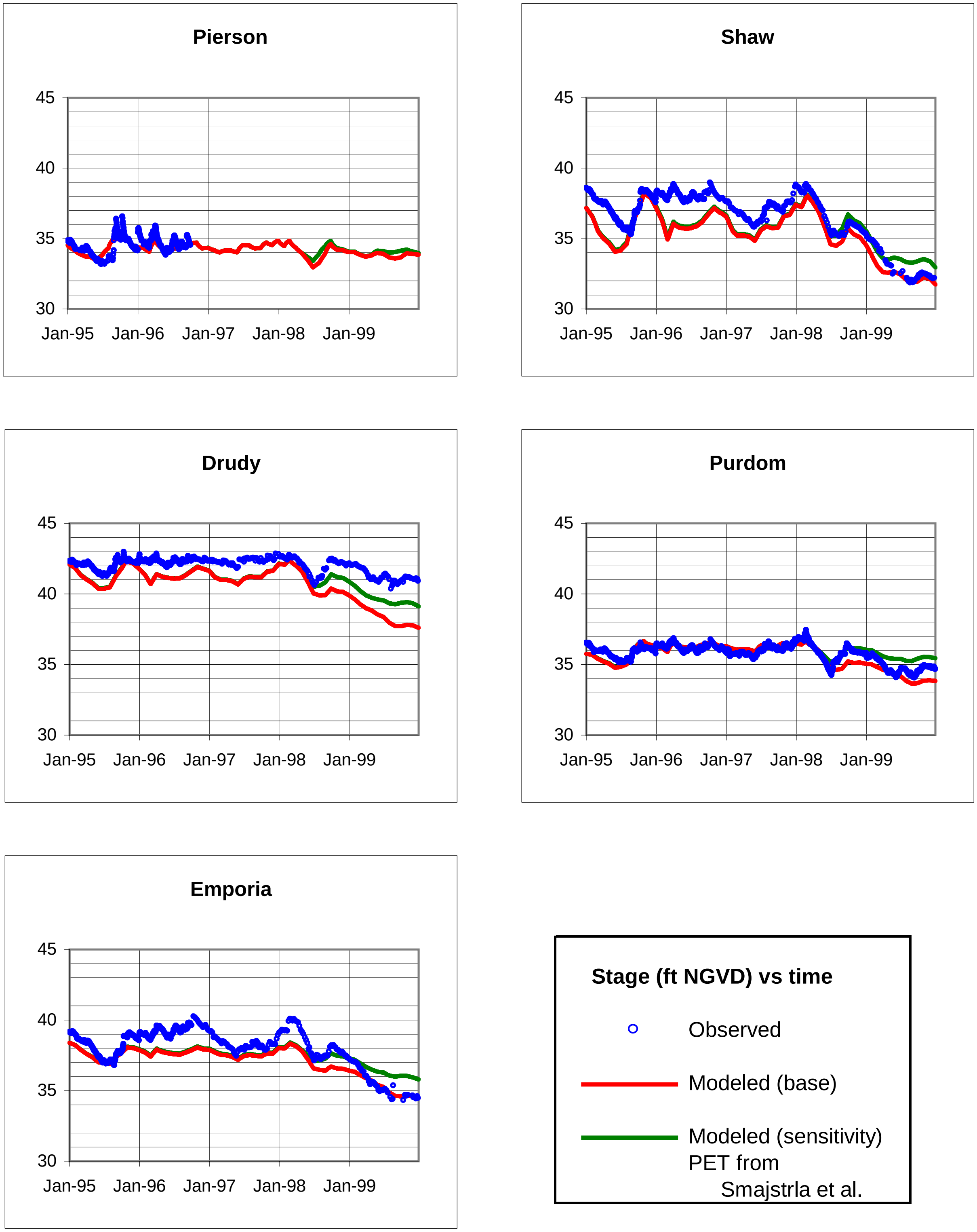

Figure 49. Sensitivity of Lake Levels to Reduced PET

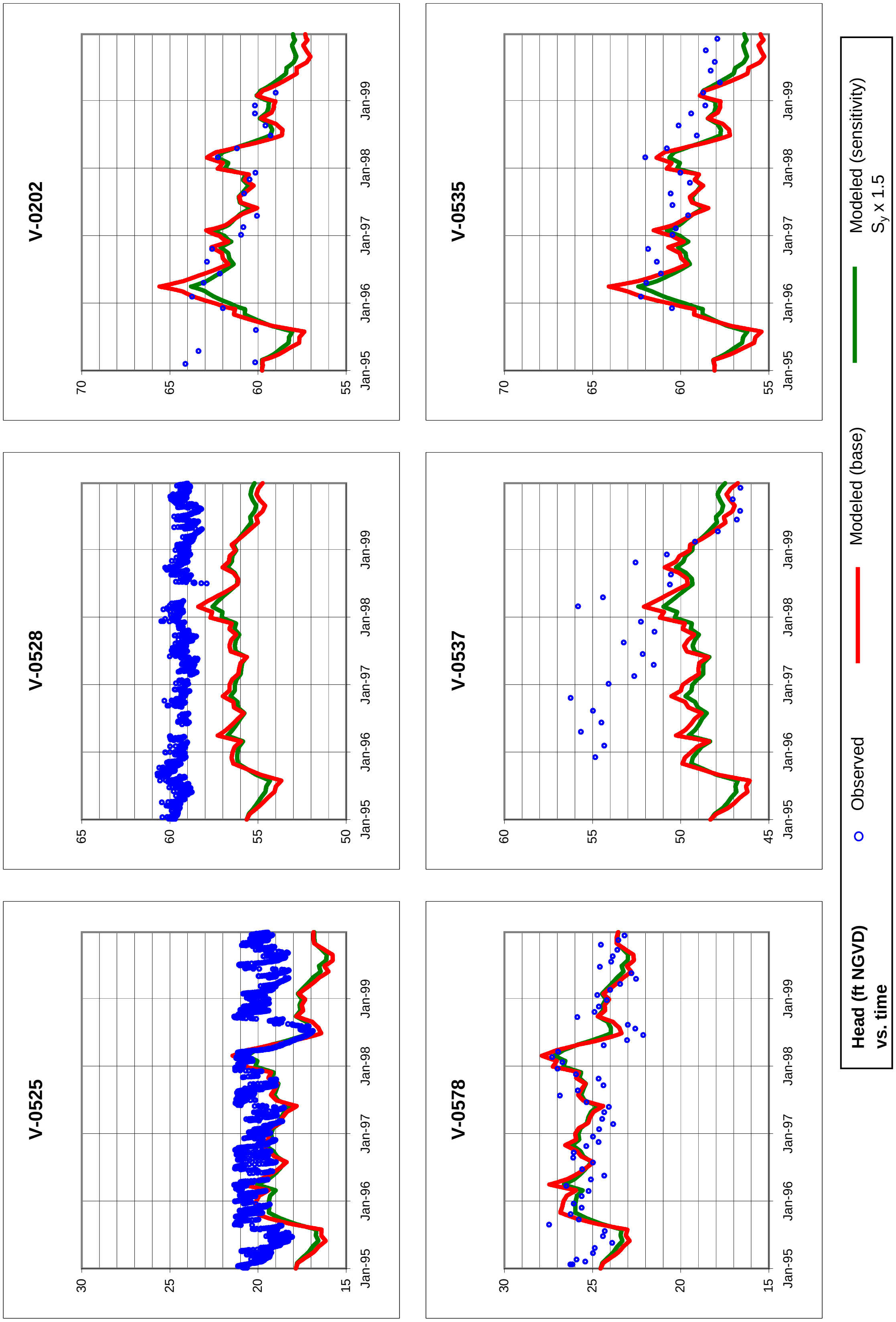

Figure 50. Sensitivity of SAS Wells to Increased Specific Yield

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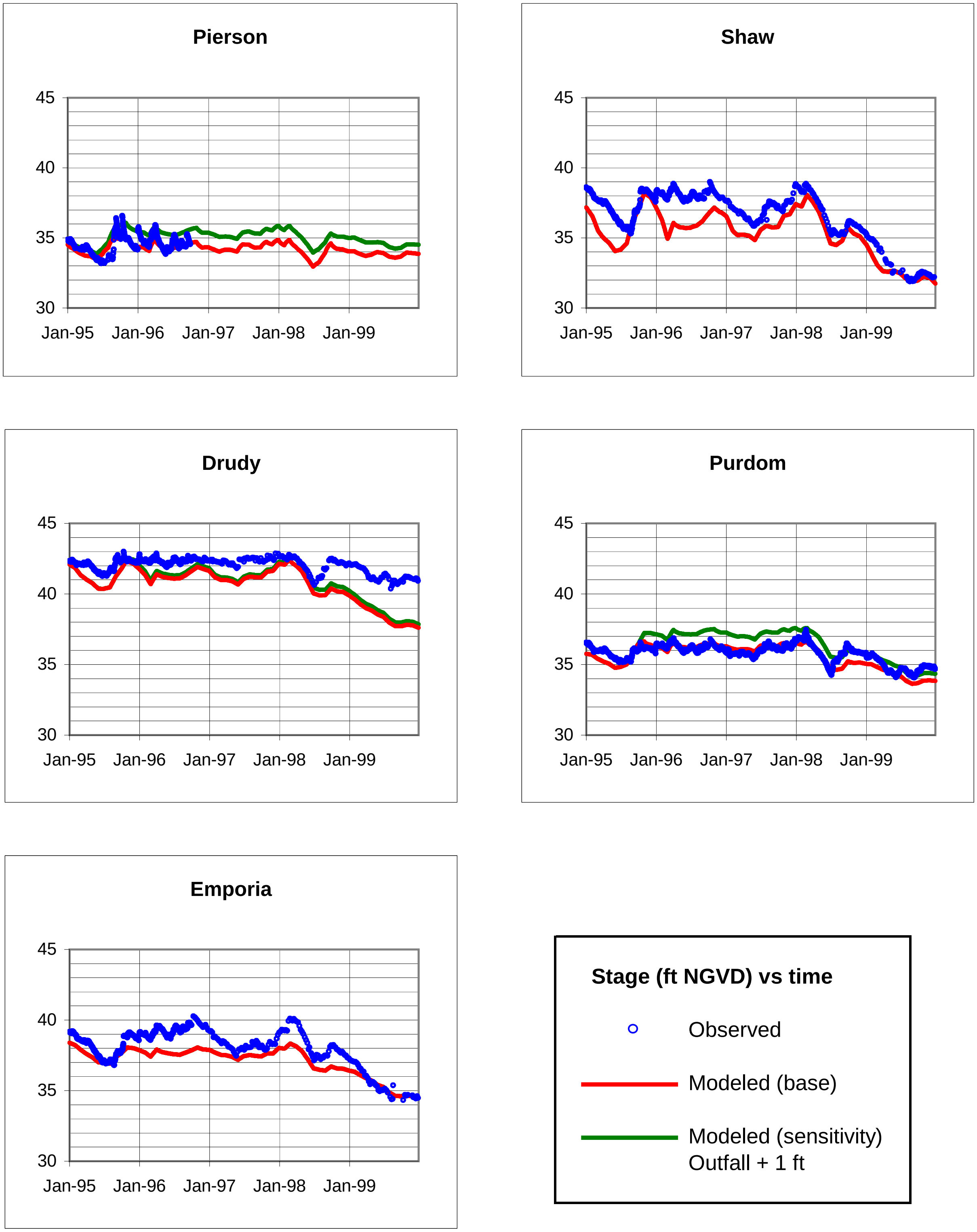

Figure 51. Sensitivity of Lake Levels to Increased Outfall Elevations

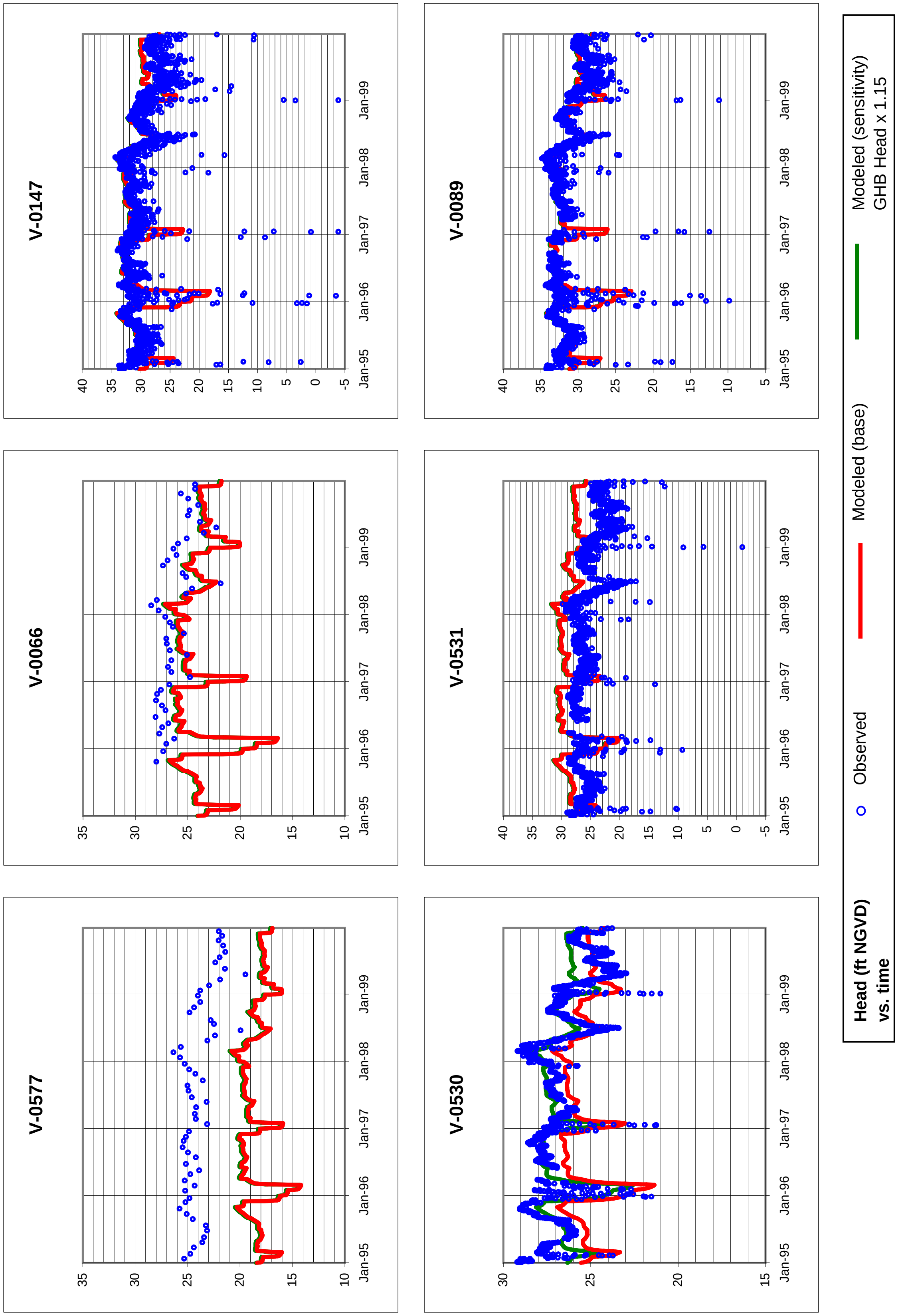

Figure 52. Sensitivity of Floridan Wells to Increased GHB Values

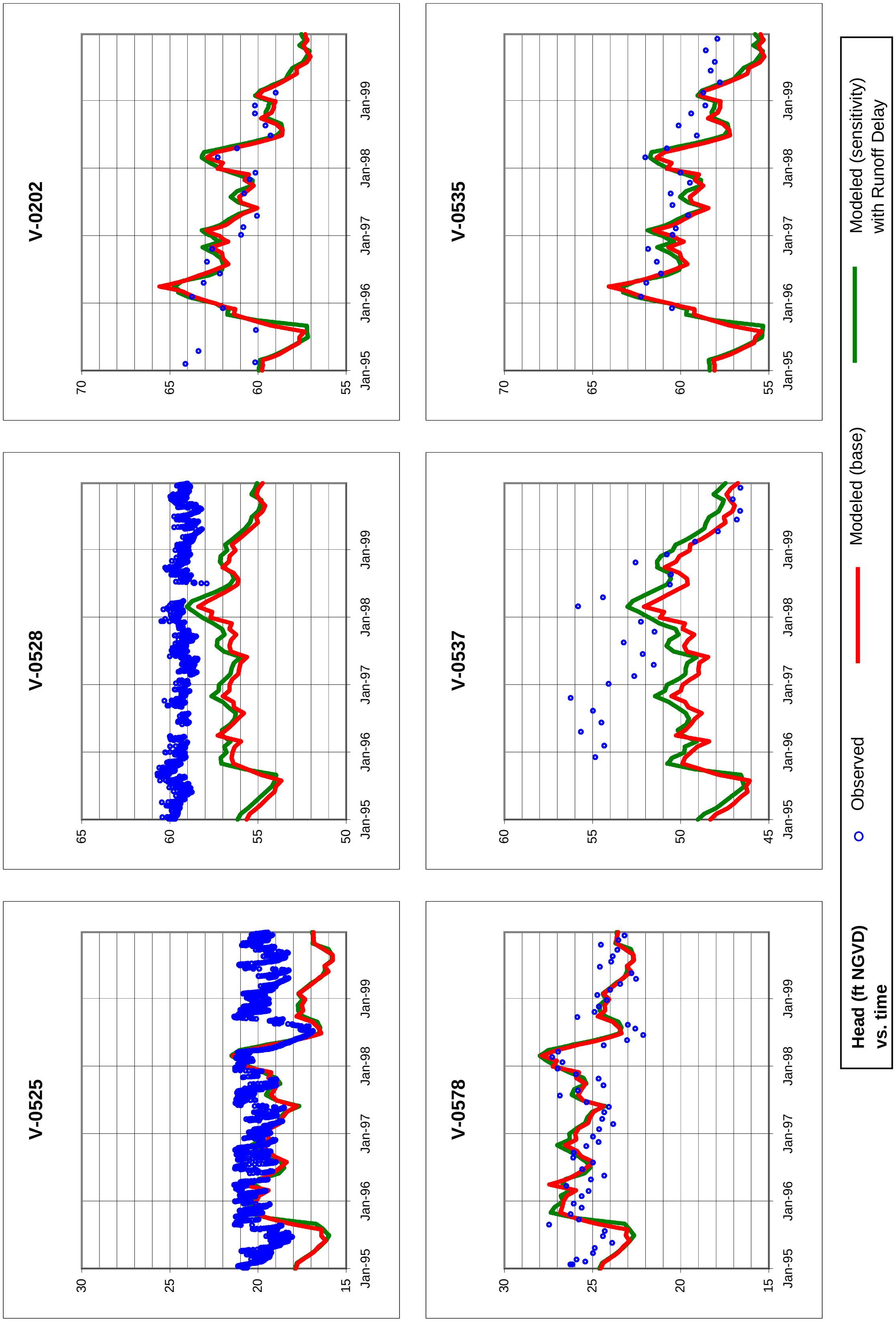

Figure 53. Sensitivity of SAS Wells to Runoff Delay Time

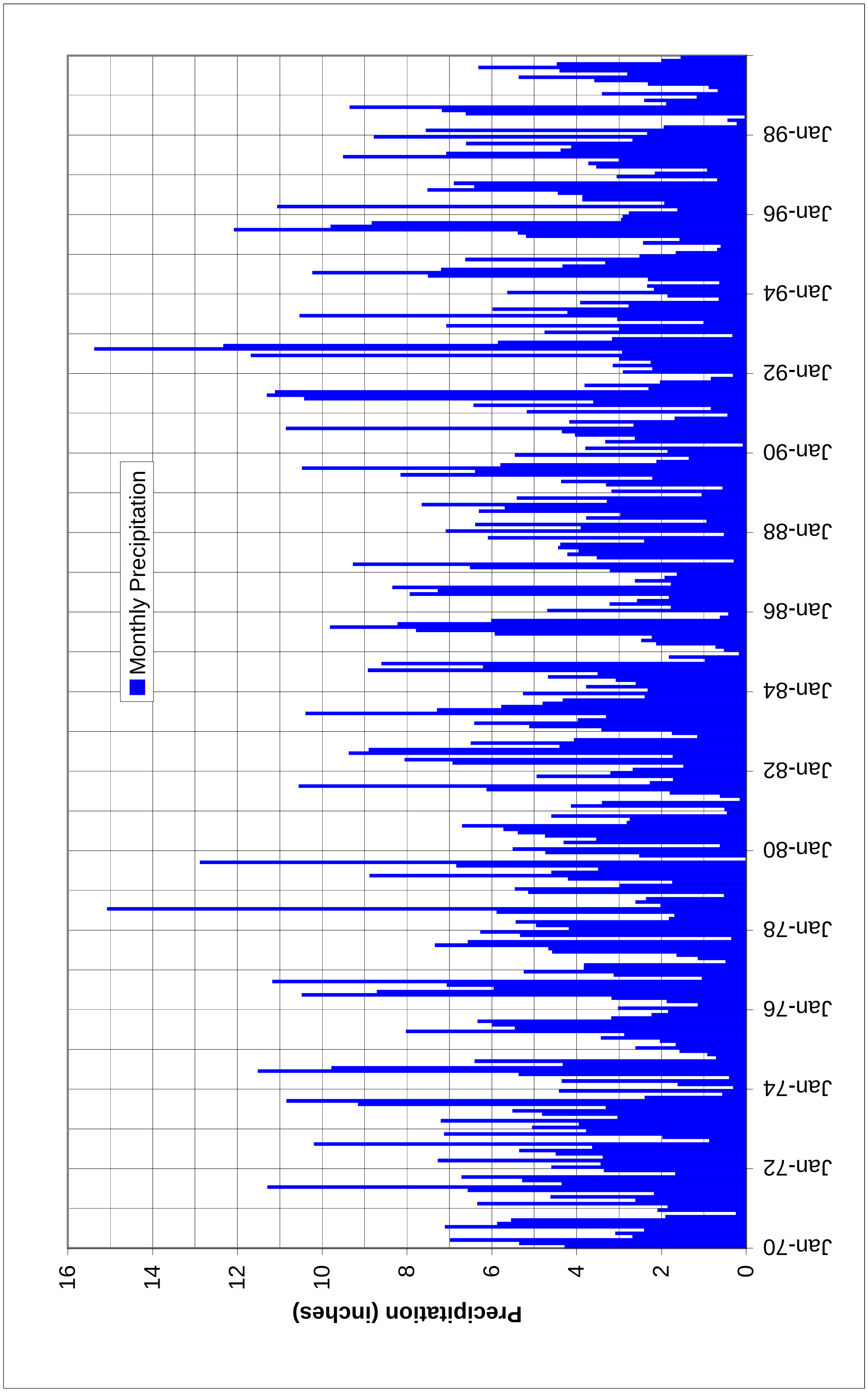

Figure 54. Precipitation at Pierson Airport, 1970-1999

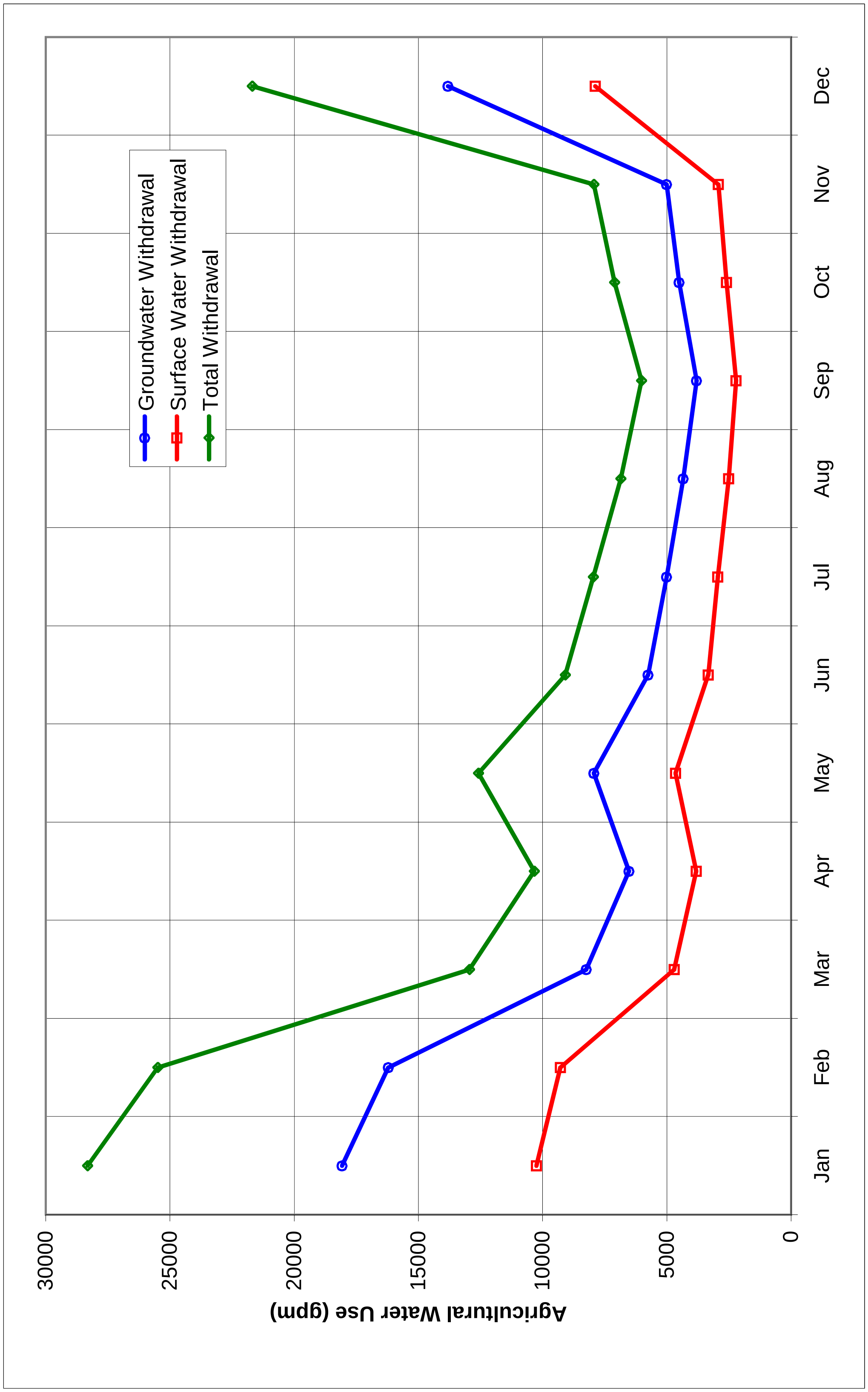

Figure 55. Average Monthly Agricultural Water Use

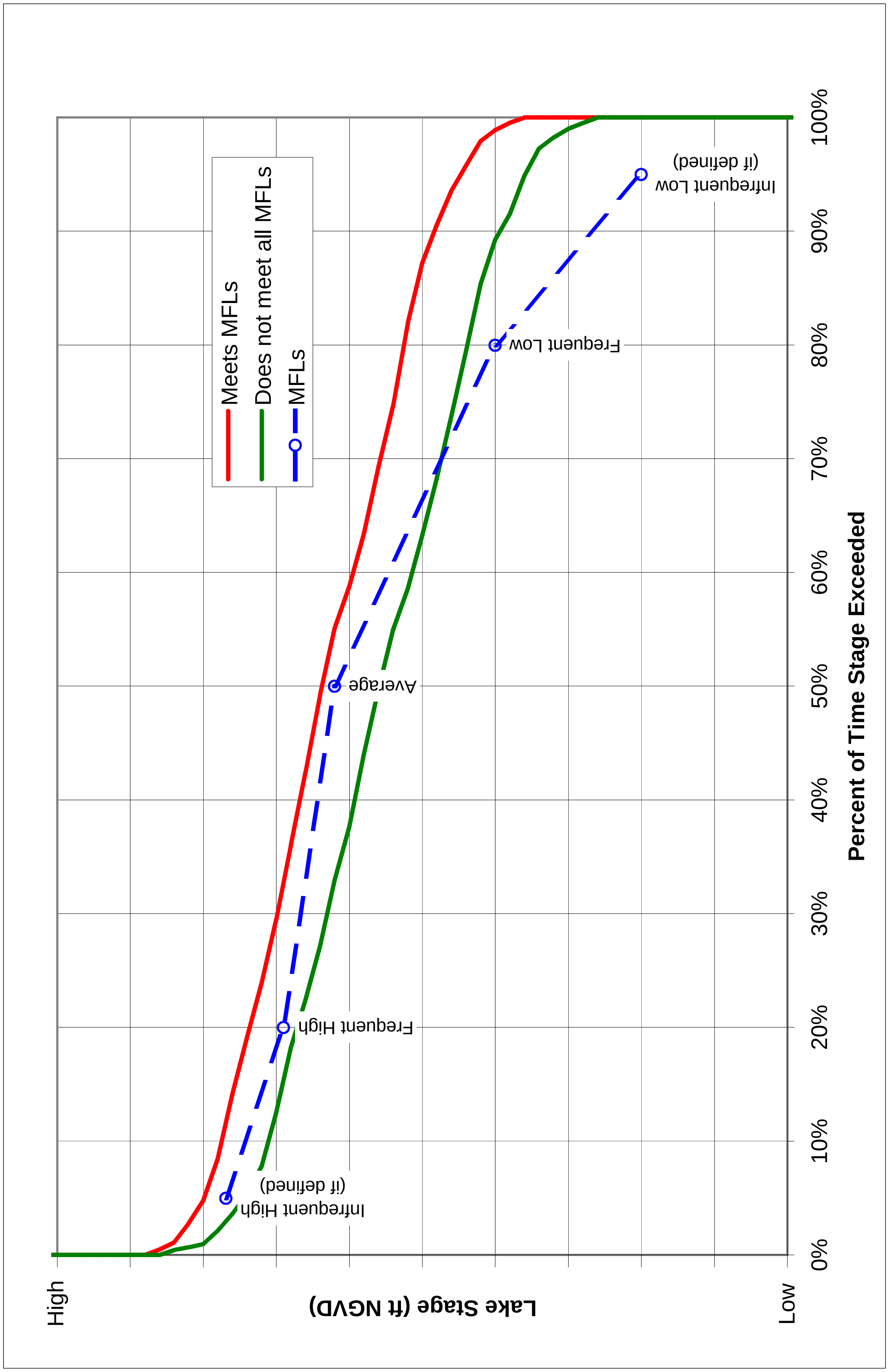

Figure 56. Hypothetical Comparison of Simulation Results to MFLs

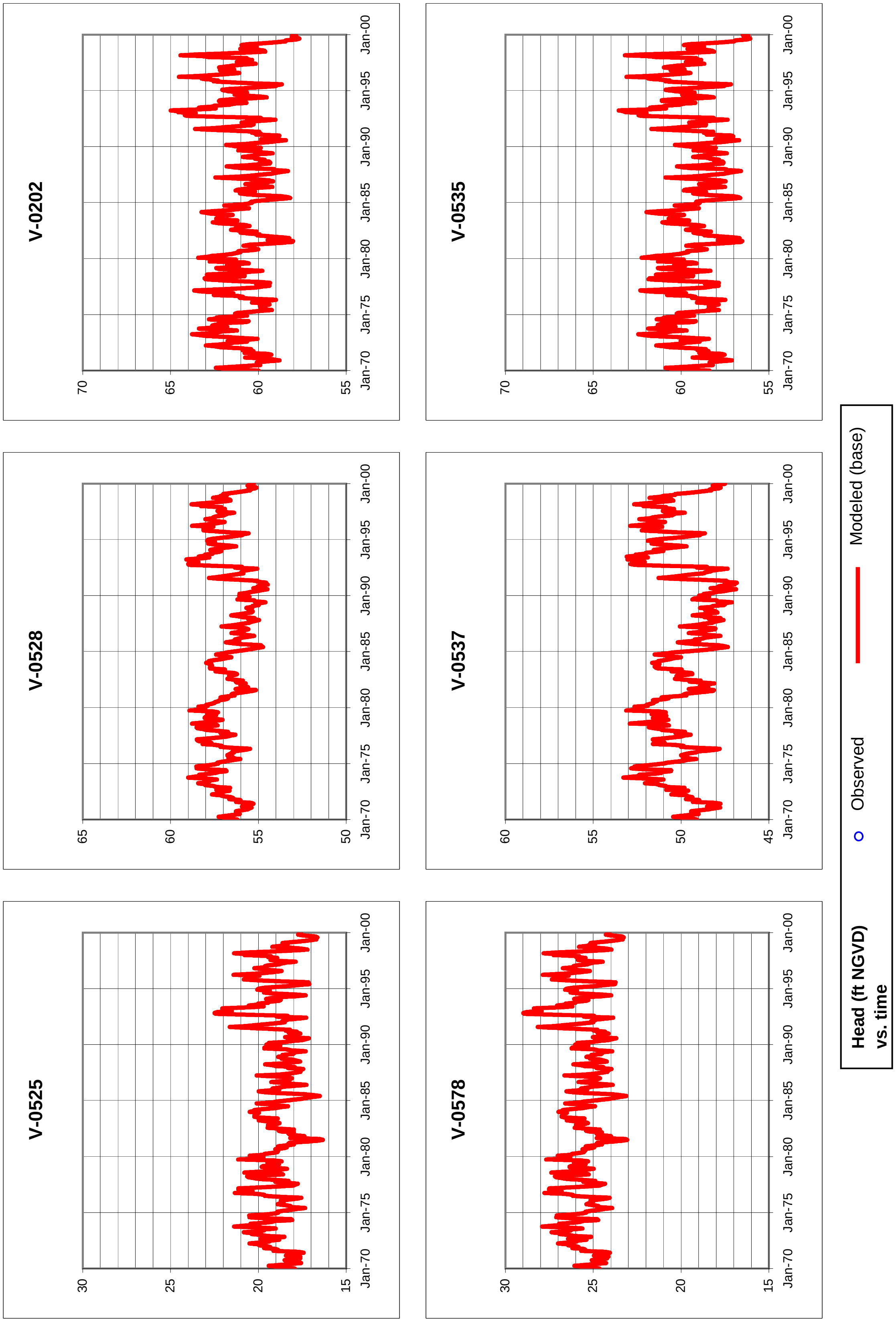

Figure 57. Simulated SAS Well Hydrographs for the Base Case Predictive Scenario

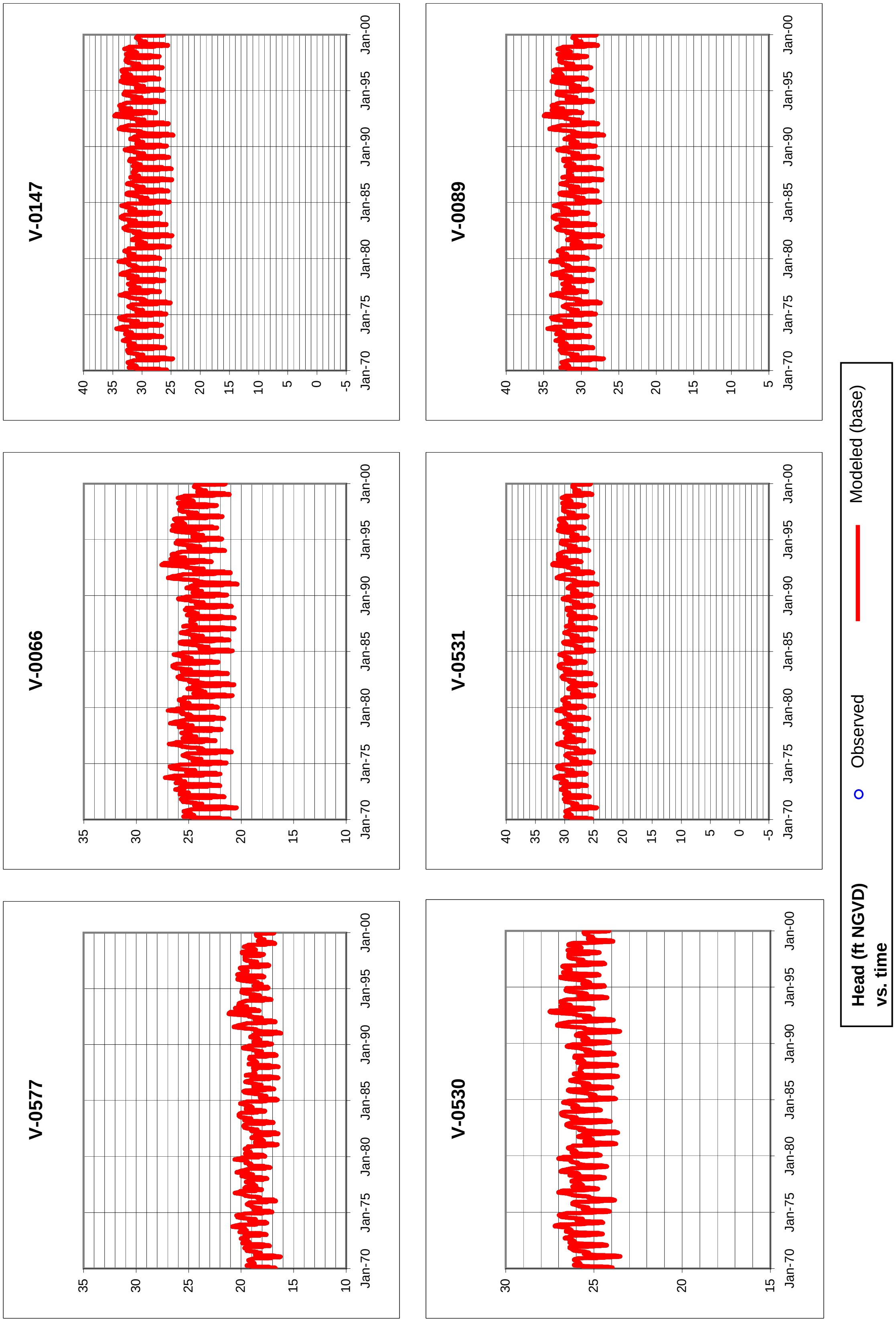

Figure 58. Simulated Floridan Well Hydrographs for the Base Case Predictive Scenario

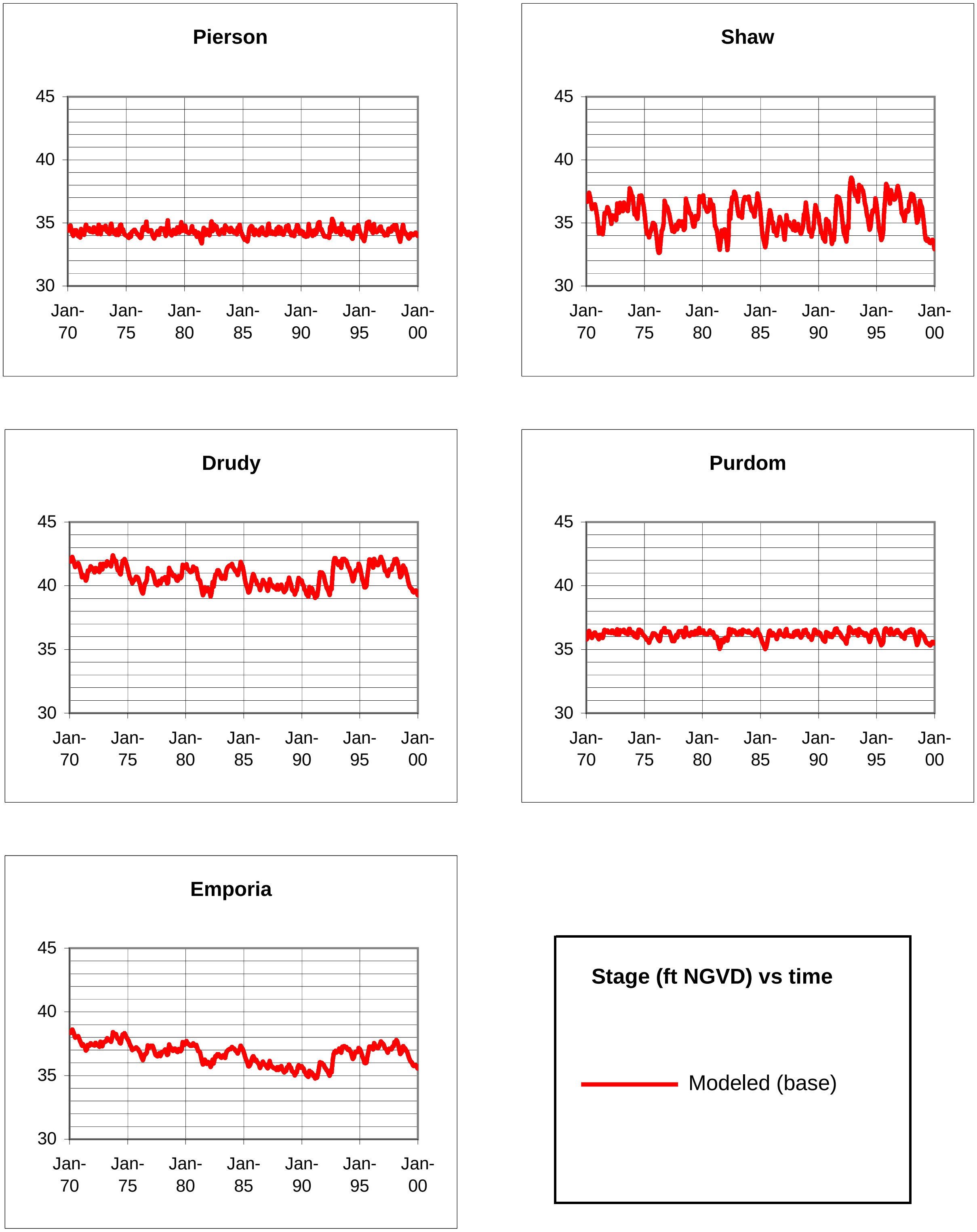

Figure 59. Simulated Lake Stage Hydrograph for the Base Case Predictive Scenario

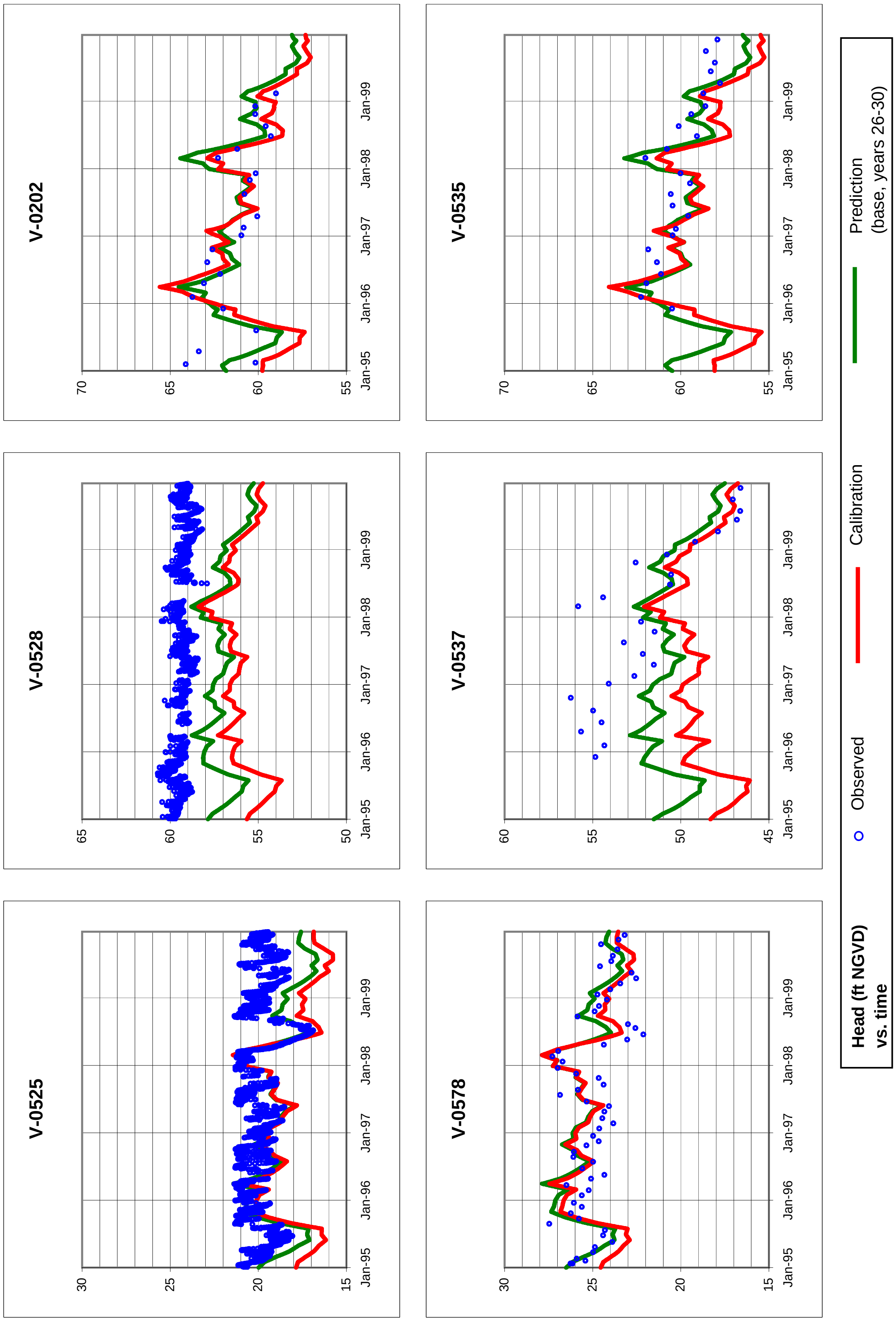

Figure 60. Comparison of Calibration Results to Predictive Results, SAS Wells

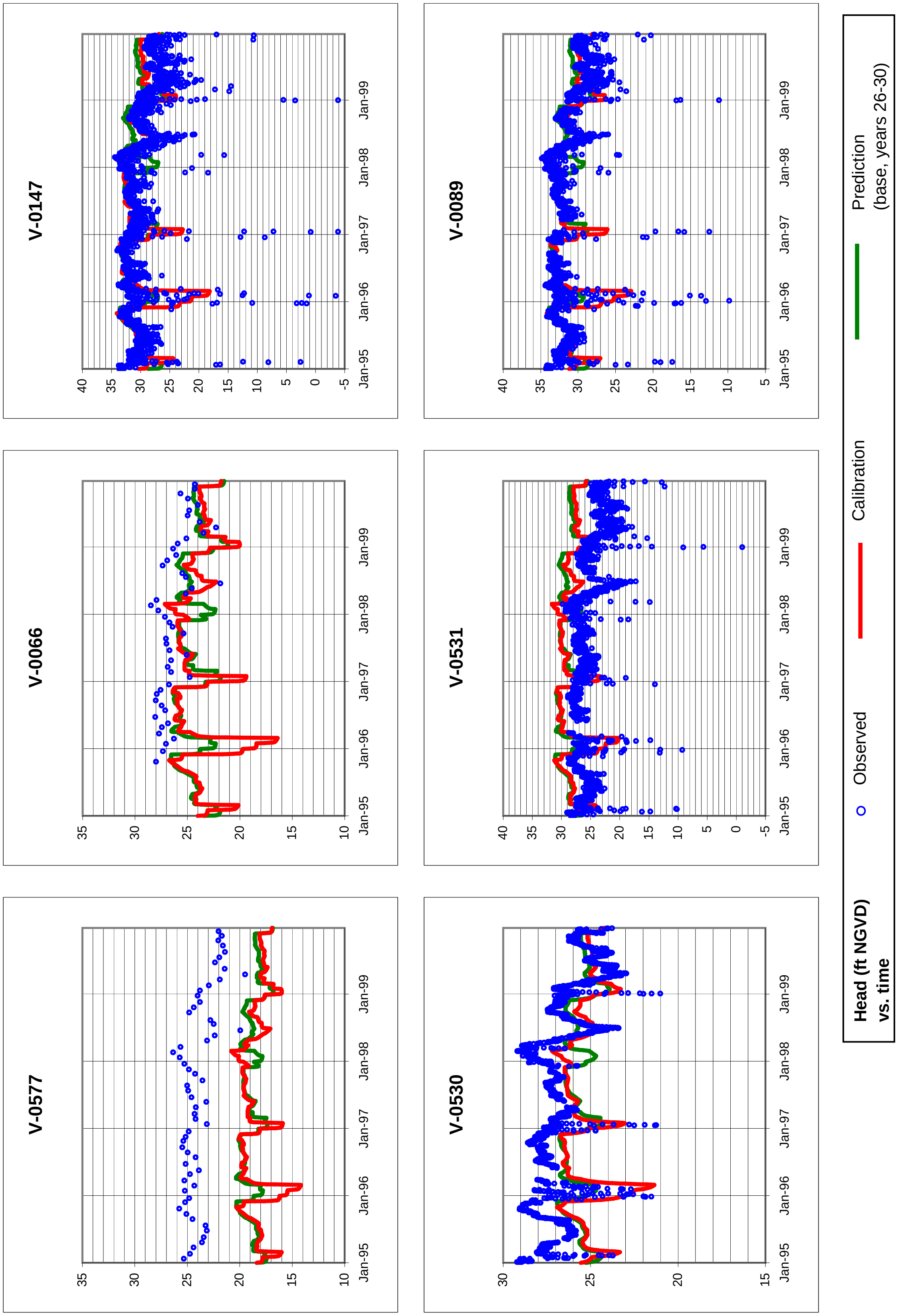

Figure 61. Comparison of Calibration Results to Predictive Results, Floridan Aquifer Wells

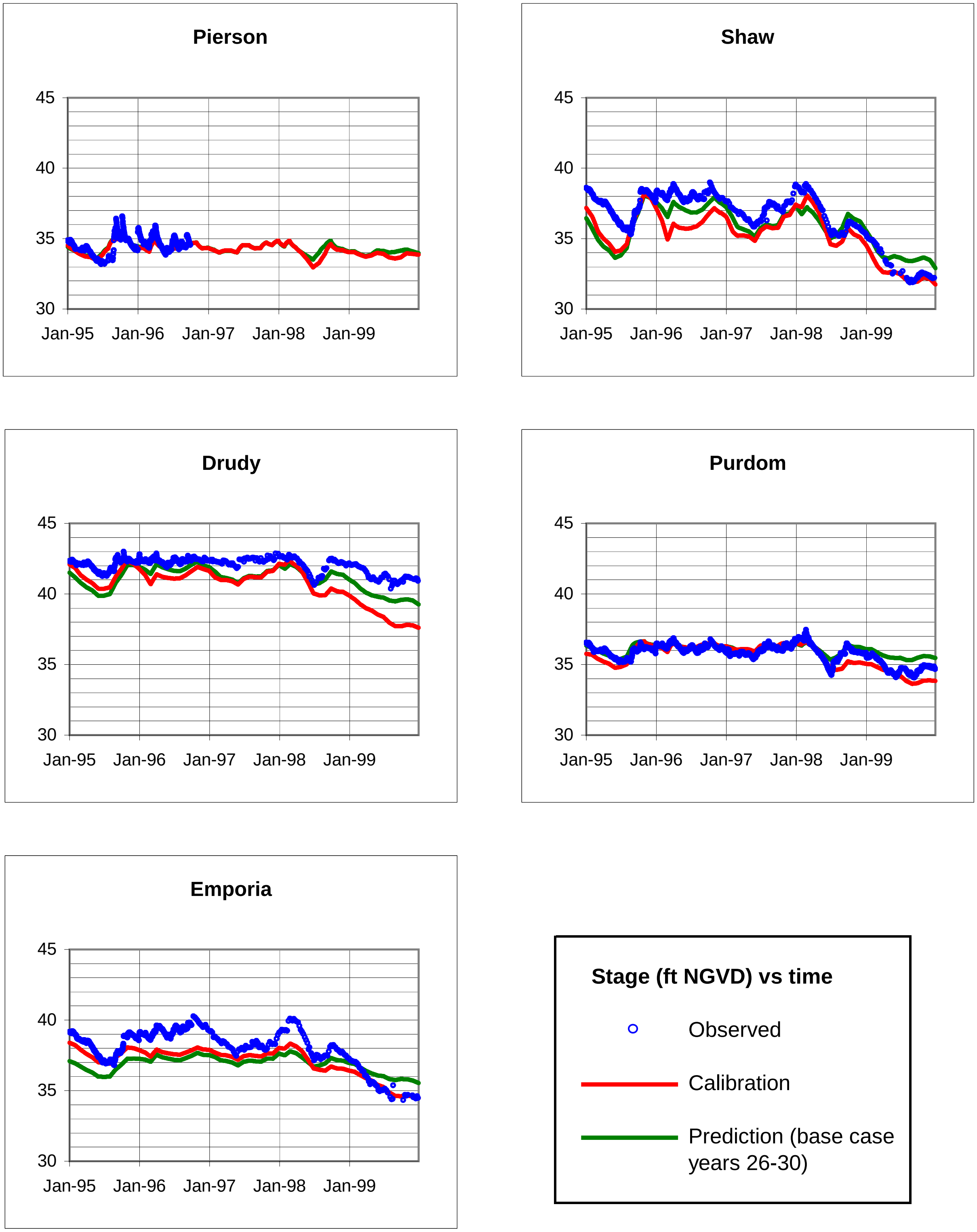

Figure 62. Comparison of Calibration Results to Predictive Results, Lake Stage

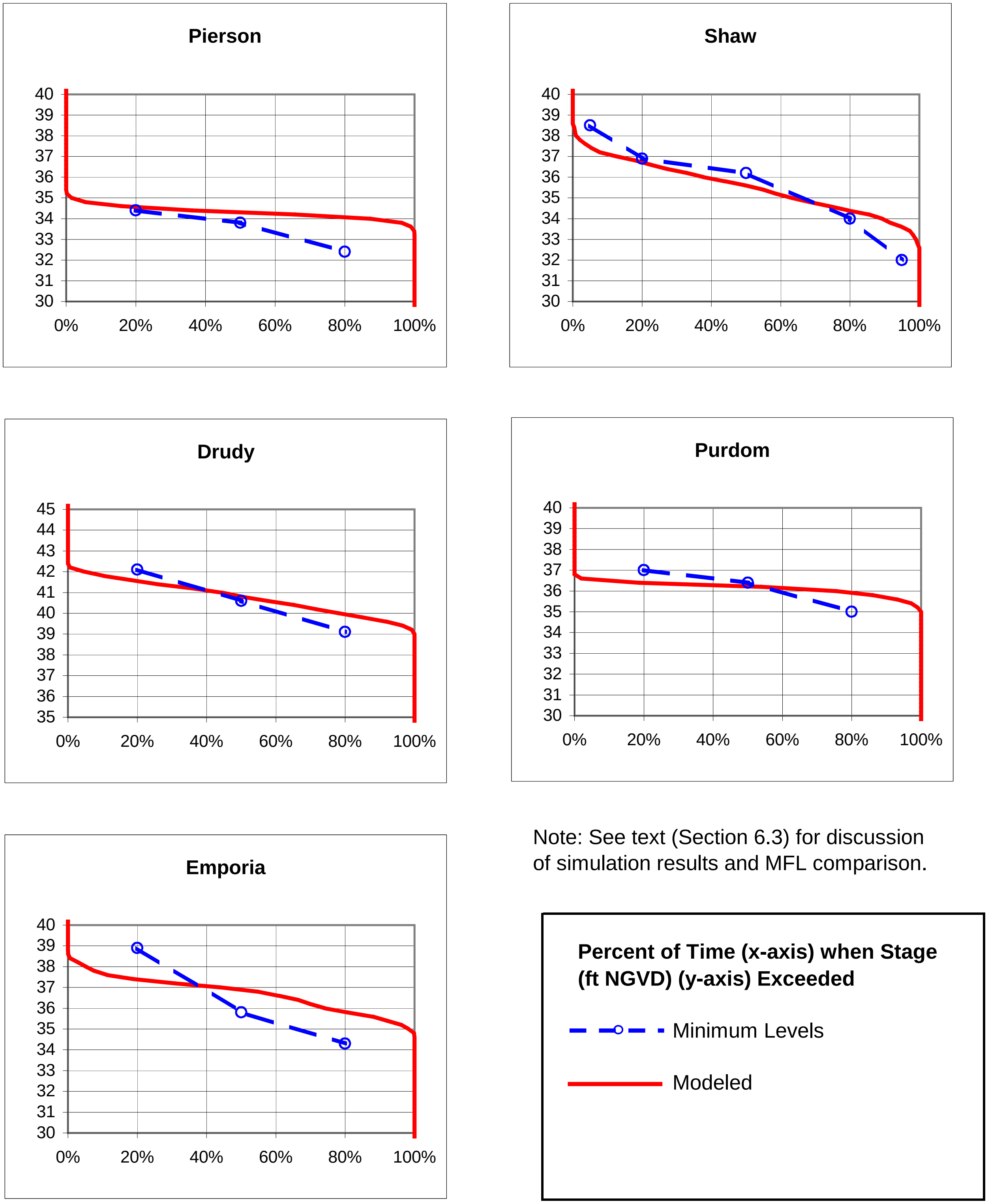

Figure 63. Simulated Stage-Duration Curves for the Base Case Scenario

Figure 64. Simulated Lake Levels during Periods of Extreme Wet and Dry Conditions

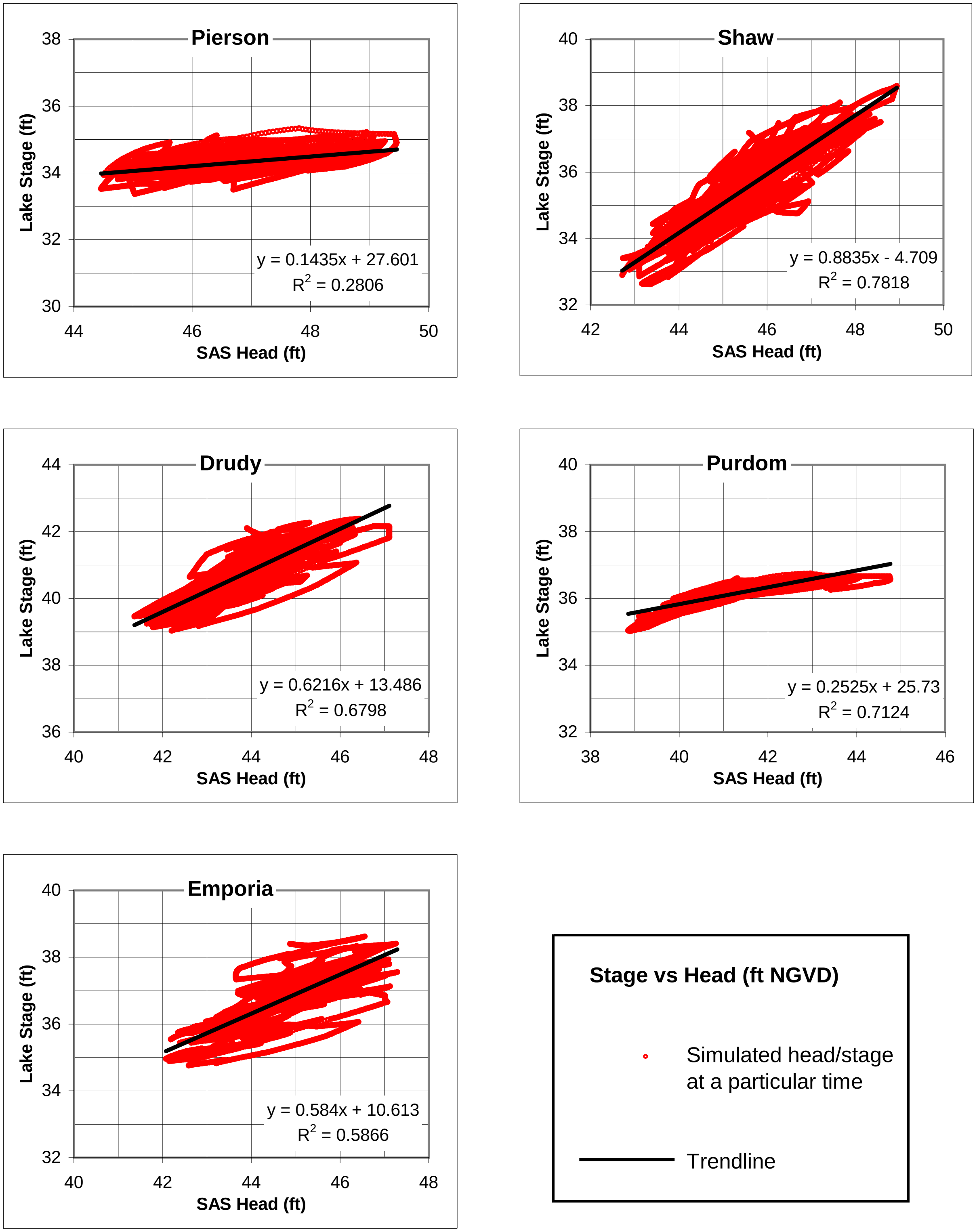

Figure 65. Correlation between Simulated Lake Stage and Simulated SAS Head

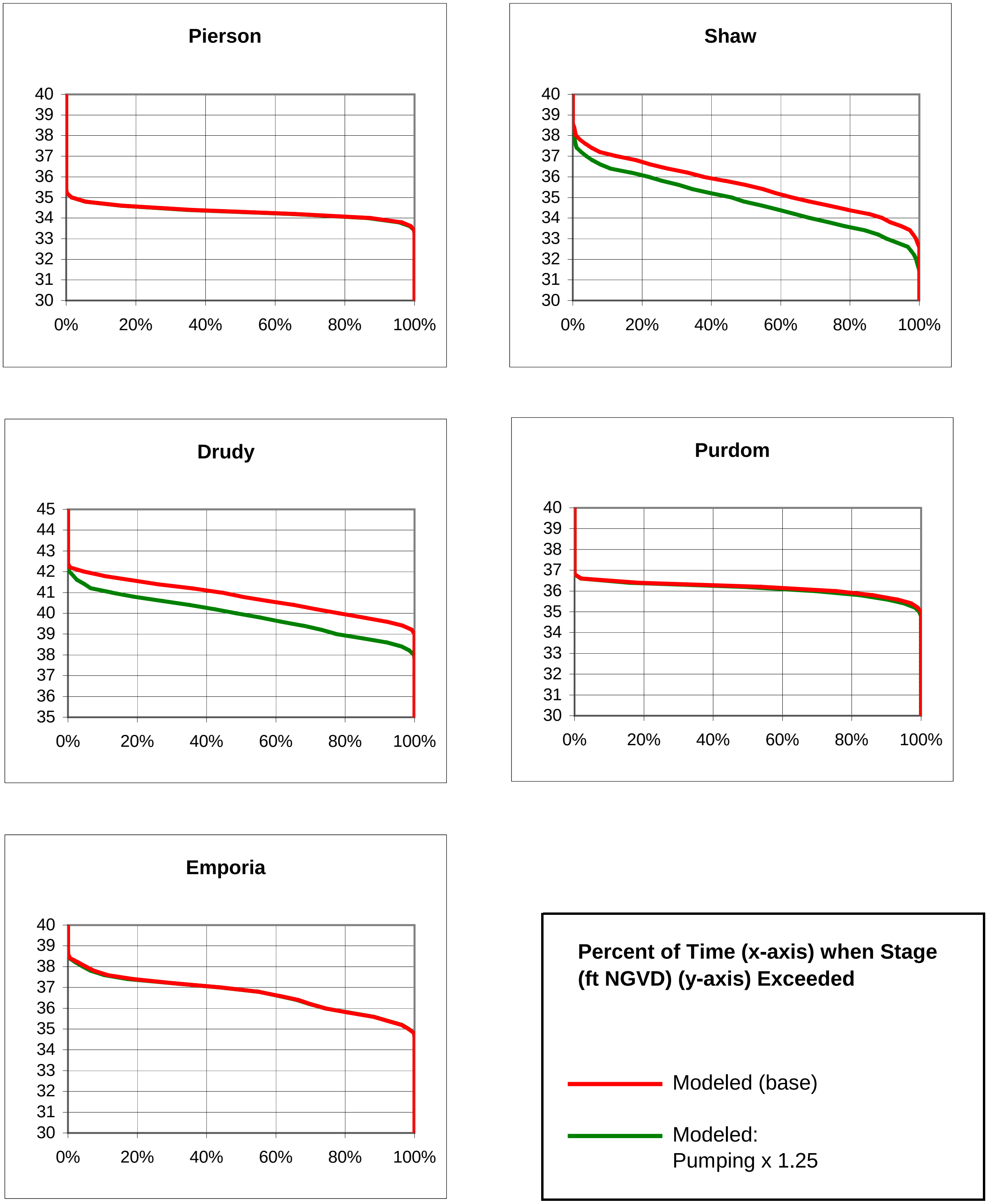

Figure 66. Simulated Stage-Duration Curves for the Increased Pumping Scenario

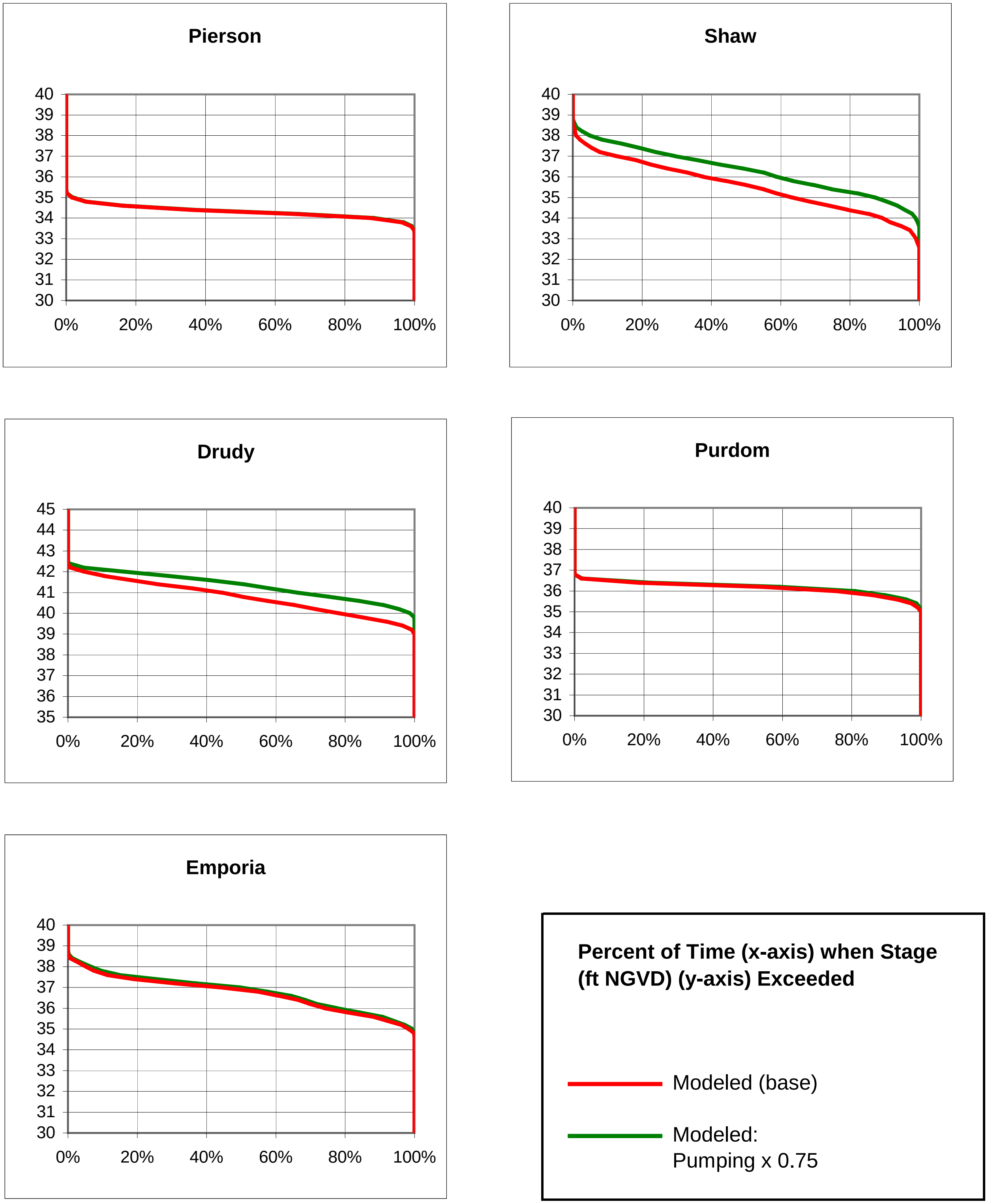

Figure 67. Simulated Stage-Duration Curves for the Decreased Pumping Scenario

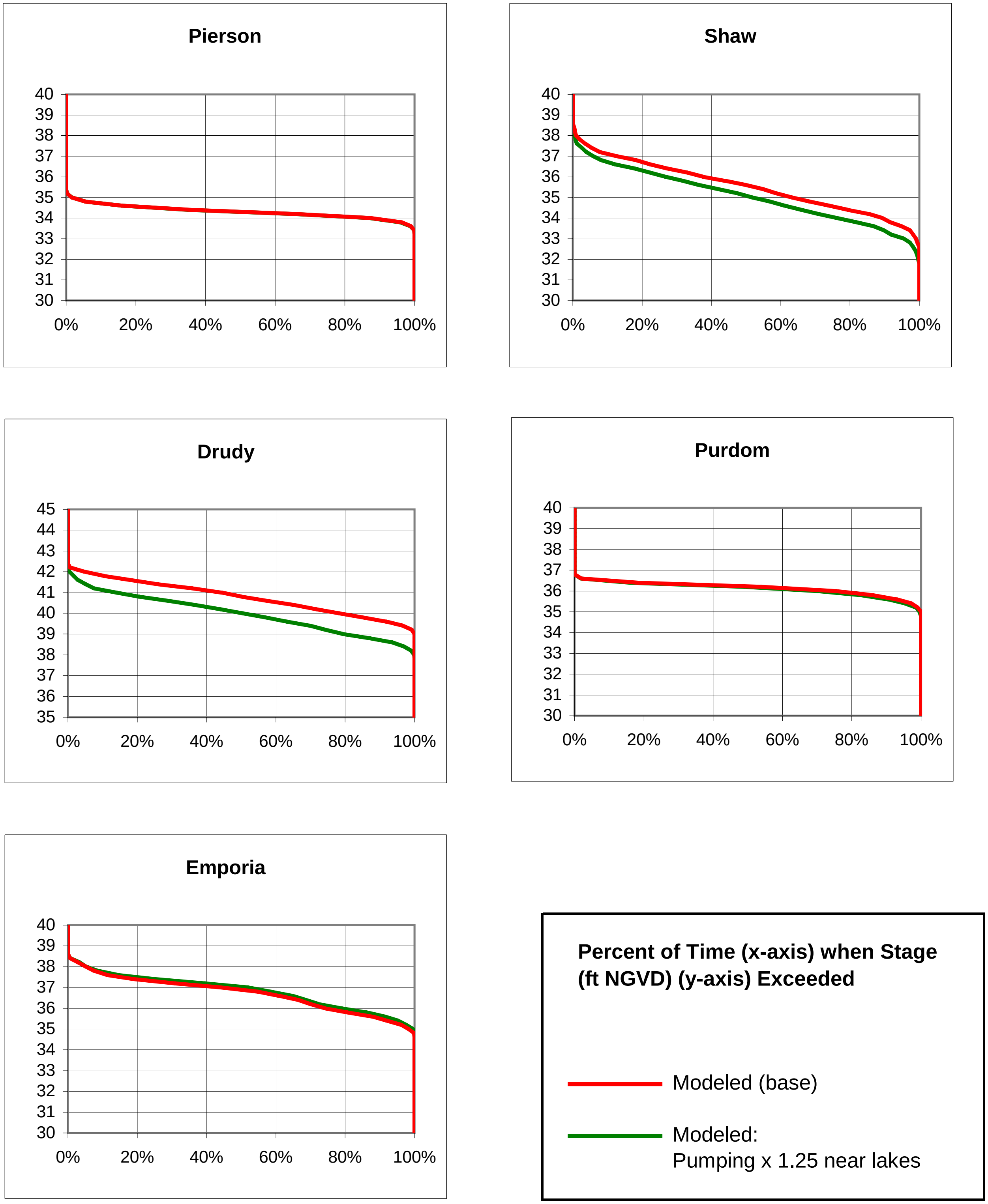

Figure 68. Simulated Stage-Duration Curves for the Increased Pumping (near Lakes Only) Scenario

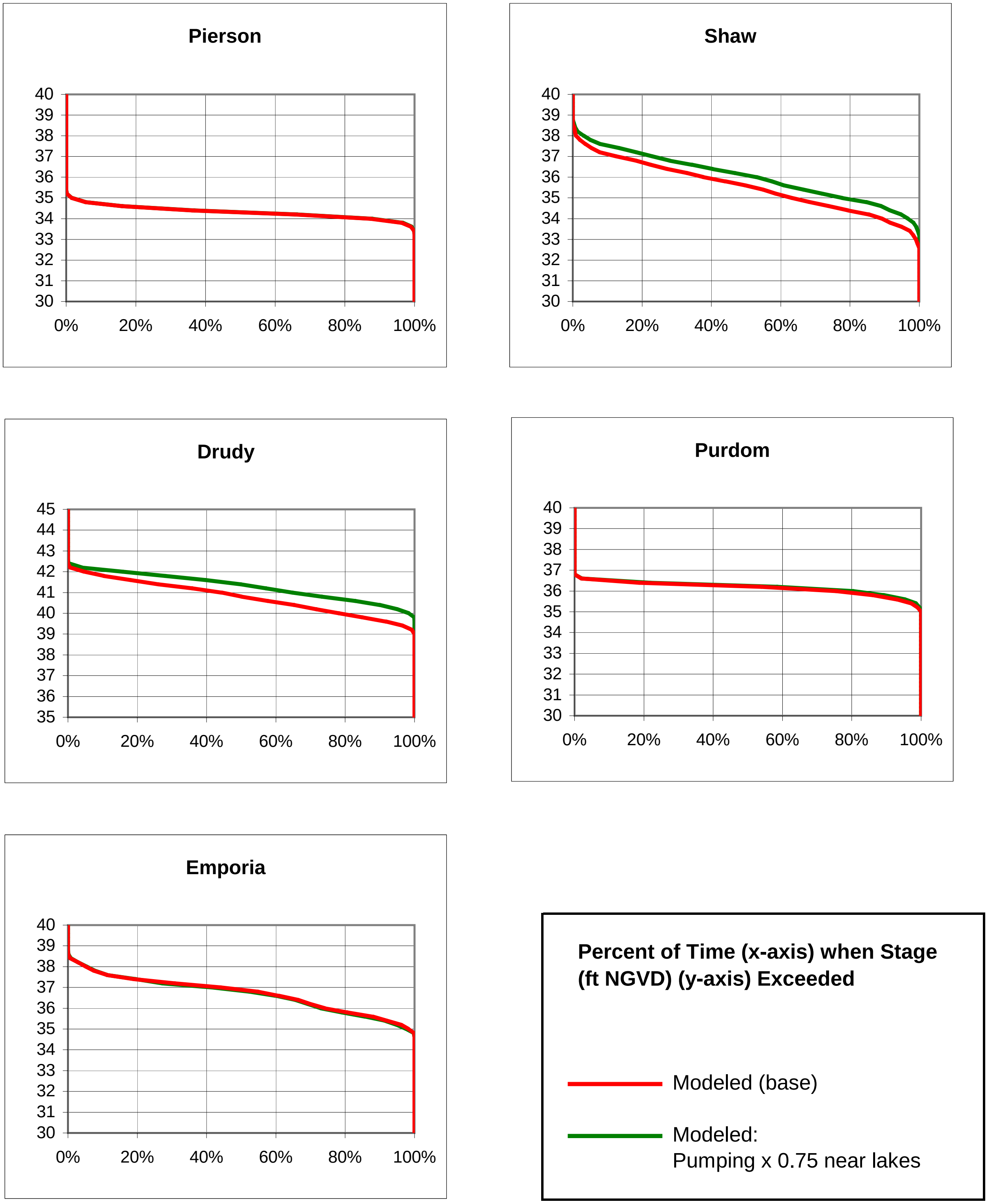

Figure 69. Simulated Stage-Duration Curves for the Decreased Pumping (near Lakes Only) Scenario

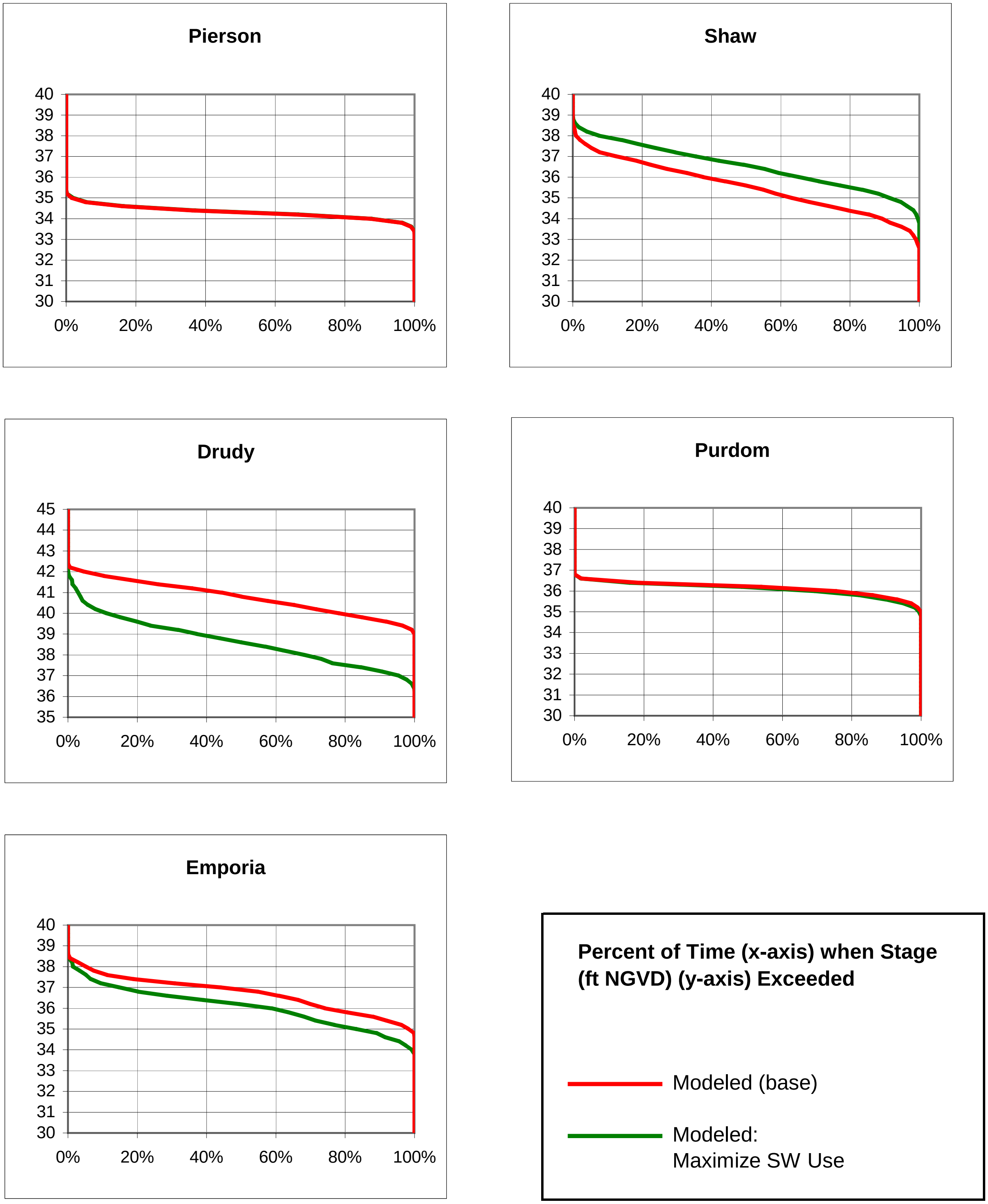

Figure 70. Simulated Stage-Duration Curves for the Maximized Surface-Water Use Scenario

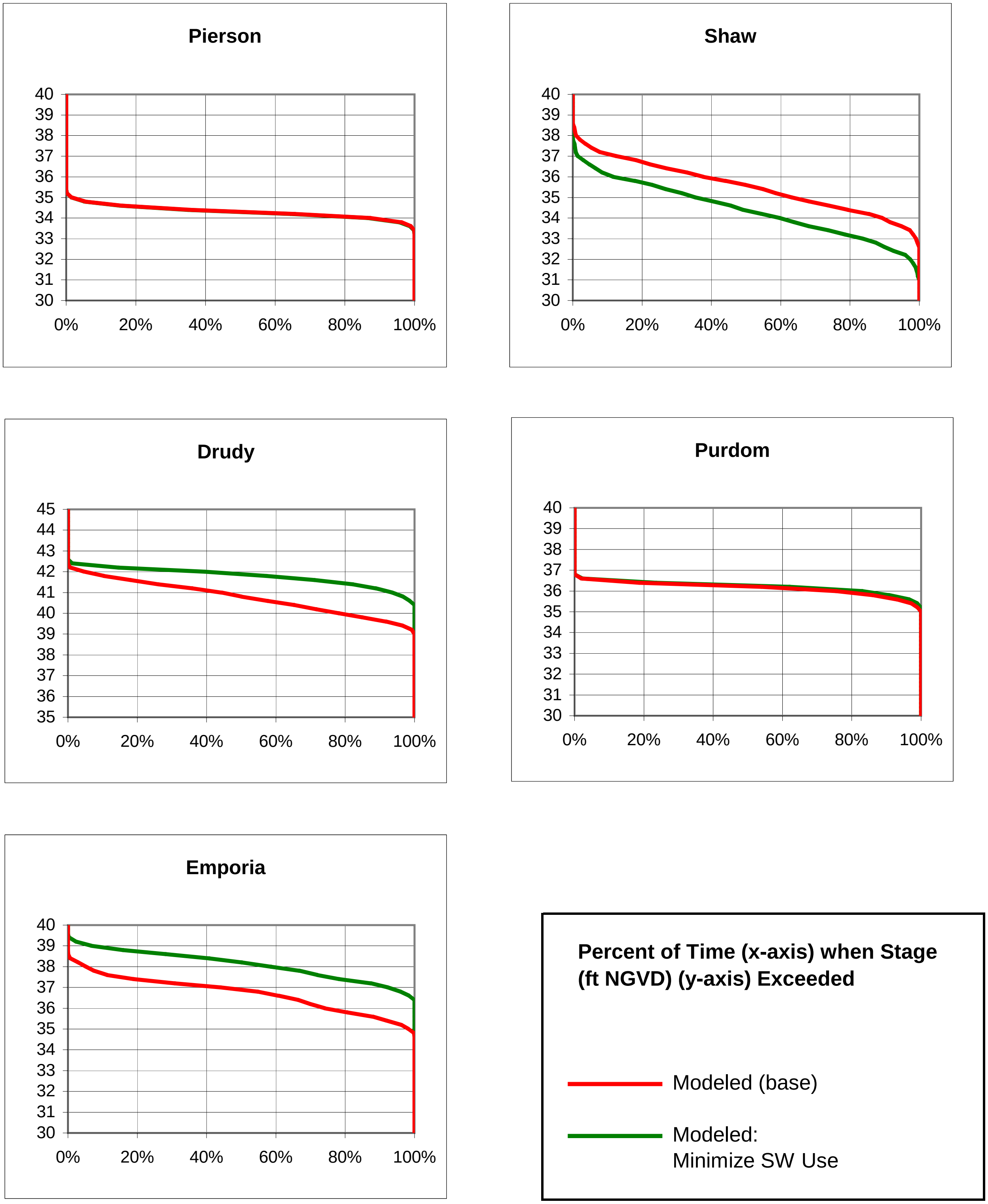

Figure 71. Simulated Stage-Duration Curves for the Minimized Surface-Water Use Scenario