Appendix B
Sacramento Valley Finite-Element Groundwater Model Documentation

APPENDIX B

Documentation of the SACFEM Groundwater Flow Model

Implementation of conjunctive water management within the Sacramento Valley is one strategy being used to enhance the reliability of the existing water supply, as well as potentially improve water quality, within the San Francisco Bay-Delta. However, the operation of conjunctive water management, or groundwater substitution projects, can result in adverse impacts on water resources within the valley. The two most critical potential impacts of additional groundwater production are depression of local groundwater levels, with associated impacts on well yields from nearby water supply wells, and changes in the hydraulic relationship between the surface water and groundwater systems in the area. To support the evaluation of these potential impacts, a high-resolution, numerical groundwater modeling tool was developed to estimate the impacts of potential future conjunctive water management projects on surface water and groundwater resources within the Sacramento Valley. This model, known as the Sacramento Valley Finite Element Groundwater Model (SACFEM), is documented herein.

1.0 Model Code Description

MicroFEM (Hemker, 1997), a finite-element based, three-dimensional, integrated groundwater modeling package developed in The Netherlands, was chosen to simulate the groundwater flow systems in the Sacramento Valley Groundwater Basin. The current version of the program (4.003) has the ability to simulate up to 25 layers and 250,000 surface nodes. MicroFEM is capable of modeling saturated, single-density groundwater flow in layered systems. Horizontal flow is assumed in each layer, as is vertical flow between adjacent layers.

MicroFEM was the chosen modeling platform for the following reasons:

- The finite-element scheme allowed the construction of a model grid covering large geographic areas (over 5,955 square miles in the Sacramento Valley Groundwater Basin) with coarse node spacing outside of the simulated project areas and finer node spacing in areas of interest (e.g., near potential project areas). The finer node spacing near simulated production wells provides greater resolution of simulated groundwater levels and stream impacts.
- The graphical interface allows rapid assignment of aquifer parameters and allows proofing of these values by graphical means.
- The flexible post-processing tools allow for rapid evaluation of transient water budgets for model simulations and identification of changes to stream discharges and other water fluxes across the model domain.

2.0 Sacramento Valley Groundwater Basin

The following briefly summarizes the geology and hydrology of the Sacramento Valley Groundwater Basin.

2.1 Geologic Setting

The Sacramento Valley Groundwater Basin is a north-northwestern trending asymmetrical trough filled with as much as 10 miles of both marine and continental rocks and sediment (Page, 1986). On the eastern side, the basin overlies basement bedrock that rises relatively gently to form the Sierra Nevada; and on the western side, the underlying basement bedrock rises more steeply to form the Coast Ranges. Marine sandstone, shale, and conglomerate rocks that generally contain brackish or saline water overlie the basement bedrock. The more recent continental deposits, overlying the marine sediments, contain fresh water. These continental deposits are generally 2,000 to 3,000 feet thick (Page, 1986). The depth (below ground surface) to the base of fresh water typically ranges from 1,000 to 3,000 feet (Bertoldi et al., 1991).

In the Sacramento Valley Groundwater Basin, groundwater users pump primarily from deeper continental deposits. Groundwater is recharged by deep percolation of applied water and rainfall, infiltration from streambeds, and lateral inflow along the basin boundaries. The quantity and timing of snowpack melt are the predominant factors affecting the surface water and groundwater hydrology, and peak runoff in the basin typically lags peak precipitation by 1 to 2 months (Bertoldi et al., 1991).

2.2 Hydrology

The Sacramento River is the main surface water feature in the Sacramento Valley Groundwater Basin. It has several major tributaries draining the Sierra Nevada, including the Feather, Yuba, and American Rivers. Stony, Cache, and Putah Creeks drain the Coast Range and are the main westside tributaries to the Sacramento River.

3.0 Model Construction

This section discusses the development of the groundwater model grid and layering, the assignment of groundwater flux boundary conditions, and the basis for assignment of material properties to the aquifers within the model domain.

3.1 Spatial Grid

The SACFEM grid consists of 120,761 nodes and 241,001 elements (see Figure B-1). The current grid was configured to support evaluation of potential conjunctive water management projects associated with the Sacramento Valley Water Management Program; however, the SACFEM model was designed to be grid independent, and geographic information system (GIS)-based tools have been developed to build a similar model of the valley on any grid developed to support a particular application. The nodal spacing of the

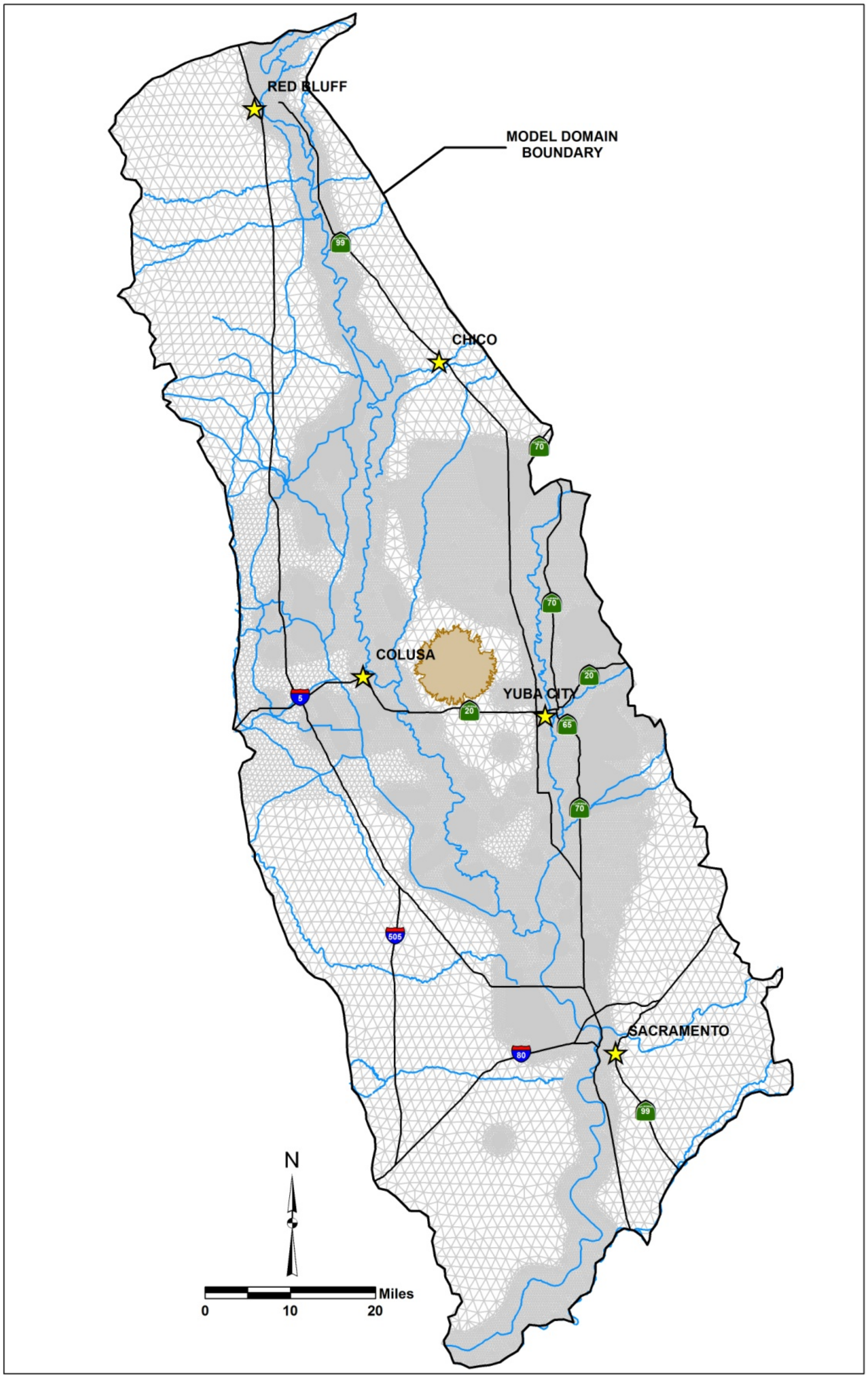

FIGURE B-1
SACFEM Finite-element Grid

current grid varies from as large as 8,200 feet (2,500 meters) near the model boundary and in areas where conjunctive water management projects are not being evaluated, to as small as 325 feet (100 meters) in areas where Sacramento Valley Water Management Program groundwater production is being evaluated. The finer node spacing near proposed project areas allows for more refined estimates of the effects of groundwater pumping on groundwater levels and groundwater/surface water interaction in the potential project areas. The model domain boundary coincides with the lateral extent of the freshwater aquifer within the Sacramento Valley Groundwater Basin.

3.2 Vertical Layering

The total model thickness is defined by the thickness of the freshwater aquifer (less than 3,000 micromhos), as defined by Berkstresser (1973) and subsequently refined in the northern portion of the valley by California Department of Water Resources (Department) (Department, 2002). For the southern portion of the model area, defined by Berkstresser data, elevation contour lines of the base of fresh water, along with information from boring locations (point measurements of the elevation of the base of fresh water), were digitized and used to generate a three-dimensional surface defining the elevation of the base of fresh groundwater. For the northern portion of the model area, the locations of geologic cross sections developed by Department Northern District staff were plotted, along with the estimated base of freshwater elevations obtained from the cross section information; and a base of freshwater elevation contour map was constructed. These data sets were then merged to yield a single interpretation of the structural contour map of the base of freshwater across the Sacramento Valley (see Figure B-2).

3.2.1 Total Aquifer Thickness

The uppermost boundary of the SACFEM model is defined at the water table. To develop a total saturated aquifer thickness distribution and, therefore, a total model thickness distribution, it was necessary to construct a groundwater elevation contour map and then subtract the depth to the base of freshwater from that groundwater elevation contour map. As discussed in more detail below, the steady-state water level calibration targets developed for this groundwater modeling tool are the steady-state groundwater heads measured in calendar year 2000. Therefore, to develop a target groundwater elevation contour map, all available groundwater elevation measurements from the year 2000 were obtained from the Department Water Data Library. These measurements were primarily collected biannually, during the spring and fall periods; and these values were averaged at each well location to compute an average water level for each location. These values were then contoured, also considering streambed elevations for the gaining reaches of the major streams included in the model, to develop a target groundwater elevation contour map for the year 2000. As described above, the distribution of the elevation of the base of freshwater was subtracted from this groundwater elevation contour map to provide an estimate of the distribution of the total aquifer thickness across the model domain.

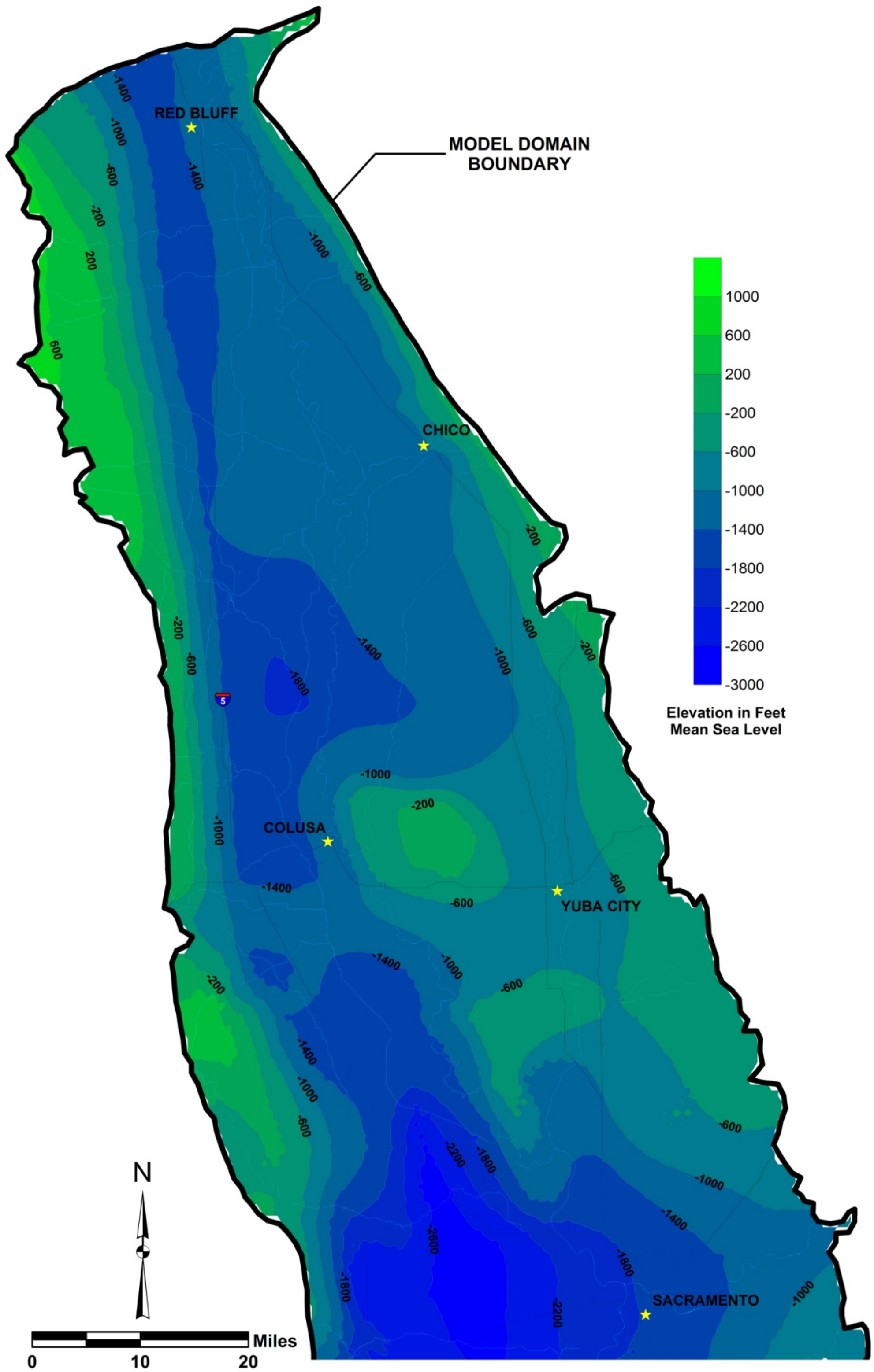

FIGURE B-2
Elevation of the Base of Fresh Water

3.2.2 Model Layer Thickness

The strategy used to develop the overall layering of the SACFEM model was to develop a tool that provided sufficient layers to assess the effects of groundwater pumping on shallow features such as wetlands and streams, but also to provide sufficient vertical resolution to allow assignment of pumping stresses to appropriate depths within the aquifer that reflect the major producing zones within the aquifer system. Another potential use of this model is to investigate potential conjunctive water management projects using the lower Tuscan aquifer, and, therefore, the layering strategy also provided for two layers explicitly representing this deep aquifer system.

Layer 1 of the SACFEM model was assigned a maximum thickness of 50 feet (15 meters). The thickness of this layer was limited to provide more accurate shallow groundwater elevations with which to support evaluations of the effects of changing groundwater levels on surface streams and wetland/riparian areas. Layers 2 through 5 represent the more regional groundwater-producing zones within the valley. The thicknesses of these layers were assigned using a specified percentage of the available aquifer thickness at a given location, to provide multiple-depth zones within which to assign regional pumping. The assumed layer thicknesses for layers 2 through 5 were also selected to reflect typical screened intervals of production wells in the Sacramento Valley. The thicknesses of layers 2 through 4 each represent approximately 10 percent of the total aquifer thickness (3 meters to 107 meters, 10 feet to 350 feet), and the thickness of layer 5 represents approximately 15 percent of the total aquifer thickness (3.5 to 193 meters, 11 feet to 633 feet).

Where the lower Tuscan aquifer is present (the northeastern and central portions of the valley), the elevation of the top of layer 6 was defined by the structural contour surface of the top of the lower Tuscan aquifer. Two layers were assigned to represent this unit because in many areas of the model, the depth to the base of fresh water (the base of the model) is as much as 900 feet below the upper surface of the lower Tuscan. Groundwater production wells drilled into the lower Tuscan would almost certainly be screened over a much smaller depth interval. To allow representation of this condition in the model, layer six was assigned a thickness of between 200 and 250 feet (60 and 76 meters), with the remaining lower Tuscan thickness assigned to layer 7. The exception to this convention is in the northeastern portion of the model near the City of Chico. The lower Tuscan outcrops in the foothills above Chico; thus, in these areas, all layers of the model represent the lower Tuscan aquifer. Moving west from Chico, a transition zone exists where a decreasing number of layers represent the lower Tuscan until it is limited to layers 6 and 7, as discussed above. In areas where the lower Tuscan is not present, the thicknesses of layers 6 and 7 represent 18 and 27 percent of the total aquifer thickness, respectively. A contour map of the total saturated aquifer thickness is presented on Figure B-3.

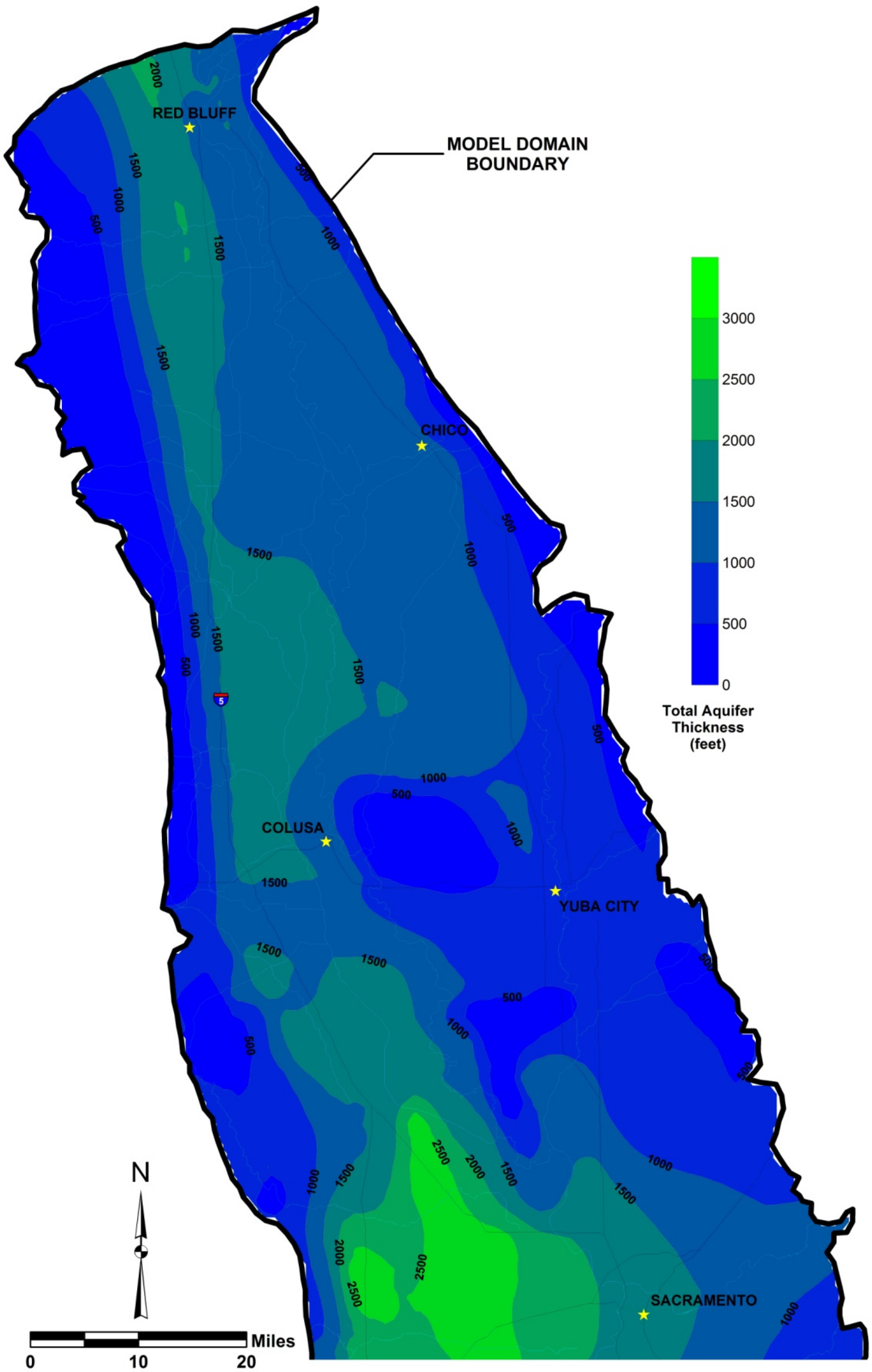

FIGURE B-3
Total Saturated Aquifer Thickness

3.3 Boundary Conditions

A combination of no-flow, specified-flux, and head-dependent boundary conditions were used to simulate the groundwater flow system within the Sacramento Valley. Each of these boundary conditions is discussed in more detail below.

3.3.1 Head-dependent Boundaries

Rivers. A head-dependent boundary condition was chosen to simulate the streams within the Sacramento Valley. The MicroFEM wadi system was used to implement streams within the model domain. MicroFEM's wadi package calculates the magnitude and direction of nodal fluxes by using the relative values of the user-specified stream stage (wh1) and the calculated head in the upper aquifer (h1), but is limited by a critical depth (wl1). When calculated groundwater elevations fall below this critical depth, it is assumed that the water table de-couples from the river system, and the leakage rate from the river to the aquifer becomes constant. The equations that govern operation of the wadi package are as follows:

Groundwater discharge to a stream is simulated if h1 > wh1:

$$Q_{outflow} = a * (h1 - wh1) / | wc1 | \quad (1)$$

In coupled streams (groundwater elevation is above the stream bottom elevation), groundwater recharge from a stream is simulated if h1 < wh1:

$$Q_{inflow} = a * (wh1 - h1) / | wc1 | \quad (2)$$

In de-coupled streams (groundwater elevation is below the stream bottom elevation), groundwater recharge from a stream is simulated if:

$$Q_{inflow} = a * (wh1 - wl1) / | wc1 | \quad (3)$$

Where:

Q	=	volumetric flux
a	=	nodal area
h1	=	simulated groundwater elevation in layer 1
wh1	=	simulated stream stage
wl1	=	stream bottom elevation
wc1	=	resistance across the streambed

Nodal area is a grid-dependent parameter that can be automatically calculated within MicroFEM. In general, the nodal area around a node that represents a discrete reach in a stream is greater than the surface area of that stream along the reach in the field. The effective resistance term (wc1) incorporates an areal correction factor to account for this discrepancy. Additionally, streambed resistance terms account for the relationship between the streambed sediments and aquifer properties in the upper half of model layer 1 when calculating stream seepage. River resistances are calculated as follows:

$$wc1 = ((Dr/Kr) +((0.5 * mt1)/Kv1))* (a/LW) \quad (4)$$

Where:

Dr	=	thickness of streambed sediments
Kr	=	vertical hydraulic conductivity of streambed sediments
mt1	=	thickness of model layer 1
Kv1	=	vertical hydraulic conductivity of model layer 1
L	=	stream length represented by the model node
W	=	field width of the wetted river channel within the stream reach represented by L

Most major streams in the Sacramento Valley were included in the groundwater flow model. Thirty-seven streams are represented. Stream locations and elevations were digitized from existing base maps and U.S. Geological Survey (USGS) topographic quad sheets, and imported into the model domain. Stream length within a given node is a grid-dependent variable calculated by MicroFEM at each river node. The stream-length term is generally overestimated by MicroFEM at stream confluences. Manual corrections of this term were made where necessary. Streambed thickness was assumed to be 3.28 feet (1 meter) for all river nodes. Assumptions of streambed vertical hydraulic conductivity were based on the type of streambed deposits expected given stream size. Wetted stream width was calculated from aerial photographs at two locations along each stream.

Drains. Drain boundary conditions were specified across the top surface of the model, excluding nodes where wadi boundaries exist. Drain boundary conditions are head-dependent boundaries that allow the transfer of water out of the model domain only. The elevation of the drain boundaries were set at the land surface. The drain boundaries were included in the model to represent a combination of surficial processes that occur in areas of shallow groundwater, including evapotranspiration and groundwater discharge to the surface.

Groundwater discharge to a drain is simulated if h1 > dh1:

$$Q_{outflow} = a * (h1 - dh1) / \mid dc1 \mid \text{ (where a = nodal area)} \quad (5)$$

Groundwater discharge to a drain is simulated if h1 < dh1:

$$Q_{outflow} = 0 \quad (6)$$

The parameter dc1 represents the drain conductance and is a measure of the resistance to flow across the drain boundary. The dc1 parameter is computed as:

$$dc1 = (Td/Kd) \quad (7)$$

Where:

Td	=	the drain interface thickness
Kd	=	the hydraulic conductivity of the drain materials

Specified-flux Boundaries. Three sets of specified-flux boundary conditions were implemented in the SACFEM model. These conditions are as follows: (1) deep percolation of applied water and precipitation along with agricultural pumping, (2) mountain-front recharge, and (3) urban pumping. Each is discussed in more detail below.

Deep Percolation of Applied Water, and Precipitation and Agricultural Pumping. The first set of specified-flux boundary conditions reflects the deep percolation of precipitation and applied water across the valley, as well as the regional agricultural pumping. The deep percolation flux values were applied to every surface node in the model. The pumping stresses due to agricultural pumping were applied at selected locations in model layers 2 through 4 (the depths of the regional producing zones across the valley). The spatial distribution and magnitudes of these fluxes were derived from the surface water budget calculations described in full detail in the Surface Water Budget section below.

Mountain-front Recharge. The second set of specified-flux boundary conditions represents the subsurface inflow of precipitation falling within the Sacramento River watershed but outside the extent of the model domain. To estimate these flux values, the USGS 10-meter Digital Elevation Model along with existing GIS-based hydrography coverages for the Sacramento Valley were used to delineate the drainage areas that are tributary to the model domain but fall outside of the watersheds of the rivers explicitly represented in the model. It is these areas that can contribute water to the model domain but are not accounted for in the wadi boundary conditions defined in the model. After the extents of these watershed areas were defined, they were intersected with PRISM (PRISM Climate Group, 2004) rainfall data using GIS tools, and the volume of precipitation falling on the watershed was computed. On the basis of the computed total volume of precipitation, the deep percolation to the groundwater system was calculated using the following empirical relationship developed by Turner (1991):

$$DP = (PPT-2.32)*(PPT)^{0.66} \tag{8}$$

Where:

DP = average annual deep percolation of precipitation (inches per year)
PPT = annual precipitation (inches per year)

A summary of the process that was used to estimate the quantity of subsurface inflow, otherwise known as mountain-front recharge, is as follows:

1. The area of each drainage basin tributary to the model domain that is not represented by streams explicitly simulated in SACFEM was computed using a GIS-based analysis of the land surface topography. The extent of these smaller watersheds is shown on Figure B-4.

2. Each drainage area polygon was then intersected with a GIS coverage of annual average rainfall estimated using the PRISM model (PRISM Climate Group, 2004). This distribution of annual average rainfall was then used to calculate the total volume of rainfall falling on the small watershed areas, and an overall average rainfall rate was computed (inches per year).

3. The average rainfall rate was then used to compute a deep percolation quantity using the relationship between annual rainfall and deep percolation rate developed by Turner (1991) and described above.

4. The annual volume of deep percolation computed in Step 3 was then converted into monthly values that were based on the monthly distribution of streamflow measured in

ungauged sections of Deer Creek. These monthly deep percolation quantities were then introduced at the model domain boundary of each small watershed polygon using injection wells into layer 1. The quantity applied to each model boundary node was proportional to boundary length of each element divided by the total boundary length of the drainage polygon.

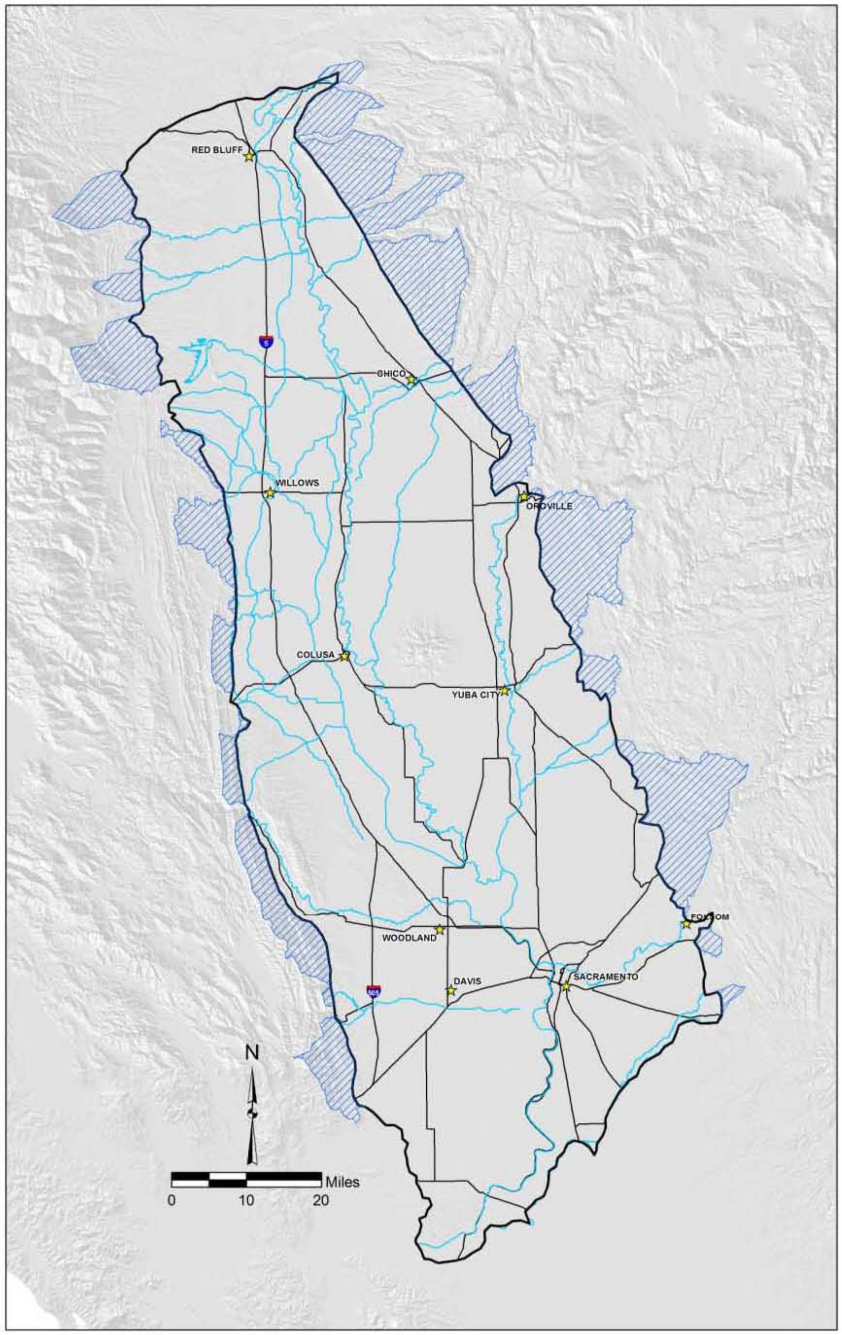

FIGURE B-4
Extent of Polygons Used to Estimate Mountain-front Recharge

Urban Pumping. The final set of specified-flux boundary conditions applied in the SACFEM model reflects urban pumping within the model domain. The distribution of agricultural pumping that was developed using the surface water budgeting methodologies described below do not include urban pumping. To estimate the quantity of urban pumping to apply to the model, the year 2000 U.S. Census data were used. Each municipal area with a population greater than 5,000 that used groundwater as a source of municipal supply was assigned a pumping volume that was based on an annual average per capita value of 250 gallons/capita/day. The urban pumping assigned to the Chico area and several northern Sacramento County municipal areas required a higher per capita rate to match the observed groundwater elevations in those areas. The monthly variability in urban pumping quantity was distributed on the basis of typical seasonal trends for municipal water use.

3.3.2 No-flow Boundaries

A no-flow boundary was specified across the bottom boundary of the model, representing the freshwater/brackish water interface.

3.4 Surface Water Budget

3.4.1 Approach

One of the most critical components to the successful operation of the SACFEM is computation of transient surface water budget components. These water budget components were estimated by using a variety of spatial information including land use, cropping patterns, source of irrigation water, surface water availability in different year types and locations, and the spatial distribution of precipitation. Surface water budget components include deep percolation of applied water, deep percolation of precipitation, and agricultural pumping.

Surface water budgets were developed by intersecting existing GIS data developed by the Department with the groundwater model grid to develop land use for each groundwater model node. Additionally, GIS data on water districts and surrounding areas were used to identify district and non-district areas. The resulting intersection provided land use, water district, and water source information for each of the over 120,000 groundwater model nodes.

3.4.2 Methodology

A semi-physically based soil moisture accounting model and historical precipitation data were used to simulate the root zone processes and calculate applied water demand and deep percolation past the root zone for each node. Calculated deep percolation was split between applied water and precipitation depending on the season and the availability of water from each source.

Calculated values for deep percolation were compared to estimated values prepared by the Department's Northern District for the year 2000. Northern District staff calculated detailed water budgets in 2000, which included some of the best available estimates of regional deep percolation. In some areas, soil parameters in the root zone model were adjusted to provide similar volumes of deep percolation. However, considerable uncertainty still exists in any estimate of regional deep percolation because soil conditions vary widely, and it is not possible to measure deep percolation on a regional basis.

The total demand for applied water was used in conjunction with the water source and water district attributes from the GIS intersection to estimate agricultural groundwater pumping. Some areas are supplied solely from groundwater, and calculated total applied water demand represents groundwater pumping. Other areas are supplied by a mix of groundwater and surface water. For these areas, estimates of the availability of surface water each year were made to determine the fraction of applied water demand met from surface water and groundwater. In these areas, additional information on the overlying water district was combined with district water rights and contracts to estimate available surface water. For example, districts within the Tehama-Colusa Canal Authority have water contracts with the U.S. Bureau of Reclamation that receive different allocations each year. An estimate of those allocations from an existing level of development simulation of Central Valley Project operations was used to calculate the availability of surface water for groundwater model elements within those districts. Any remaining applied water demand, after consideration of available surface water, is assumed to be met by groundwater pumping.

3.5 Aquifer Properties

The distribution of aquifer properties across the Sacramento Valley is poorly understood. In certain areas with significant levels of groundwater production, the collection of aquifer test data and the measurement of historical groundwater-level trends in response to known groundwater production rates have provided valuable information on aquifer properties. However, in the majority of the valley, these data are not available.

To estimate the spatial distribution of aquifer properties across the model domain for this numerical modeling effort, a database of well productivity information was used. In consultation with Department staff, a database was obtained that included all of the specific capacity yield data that were available from well log records. These data were compiled along with well construction information for each production well to yield a representative data set of well productivity across the valley. Wells that did not have available construction data were omitted from further consideration. To protect owner privacy, the exact location of each well was modified by Department staff to reflect the center of the section in which each well was located. This modification in well location did not adversely affect the use of the data to estimate the spatial distribution of aquifer properties, given the extremely large area encompassed by the model domain. Approximately 1,000 wells in the database within the model domain were used in this analysis.

The intent of the modeling analysis described herein is to simulate the effects of the operation of high-productivity irrigation wells screened within the major producing zones in the valley to support conjunctive water management projects. Therefore, the aquifer properties that are of primary interest are those of the major aquifer zones tapped by large-diameter irrigation wells. The well database described above was filtered to remove data obtained from tests on low-yield and shallow, domestic-type wells. All test data from wells that reported a well yield below 100 gallons per minute were eliminated from consideration, as were the test data from wells with a total depth of less than 100 feet. The only exception to this second consideration was for wells that were located along the basin margins – where aquifers are thin – that reported what appeared to be valid test results. Data from these wells were considered because they were often the only data available in the basin margin areas.

After the data set for consideration was finalized, the reported specific capacity data for each well were used to estimate an aquifer transmissivity for that location. The relationship used to estimate aquifer transmissivity was the following form of a simplified version of the Jacob non-equilibrium equation:

$$Sc = T/2000 \tag{9}$$

Where:

Sc = specific capacity of an operating production well (gallons per minute per foot of drawdown)

T = aquifer transmissivity (gallons per day per foot)

After a transmissivity estimate was computed for each location, the transmissivity value was then divided by the screen length of the production well to yield an estimate of the aquifer hydraulic conductivity. The final step in the process was to smooth the hydraulic conductivity field to provide regional-scale information. Individual well tests produce aquifer productivity estimates that are local in nature, and might reflect small-scale aquifer heterogeneity that is not necessarily representative of the basin as a whole. To average these smaller scale variations present in the data set, a FORTRAN program was developed that evaluated each independent hydraulic conductivity estimate in terms of the available surrounding estimates. When this program is executed, each hydraulic conductivity value is considered in conjunction with all others present within a user-specified critical radius, and the geometric mean of the available hydraulic conductivity values is calculated. This geometric mean value is then assigned as the representative regional hydraulic conductivity value for that location. The critical radius used in this analysis was 10,000 meters, or about 6 miles. The point values obtained by this process were then kriged to develop a K distribution across the model domain. The aquifer transmissivity at each model node within each model layer was then computed using the geometric mean hydraulic conductivity values at that node times the thickness of the model layer. Insufficient data were available to attempt to subdivide the data set into depth-varying hydraulic conductivity distributions, and it was, therefore, assumed that the computed mean hydraulic conductivity values were representative of the major aquifer units in all model layers. The final distribution of K used in the SACFEM model is shown on Figure B-5.

3.6 Stream Stage

The degree of interaction between surface water and groundwater systems within the valley is heavily dependent on the distribution of stream stage across the valley. Unfortunately, very limited site-specific information is available to define the stage of most of the smaller tributary streams to the Sacramento and Feather Rivers. The use of regional topographic data such as USGS Digital Elevation Model data sets is problematic because these elevations are gathered on a regular grid pattern and frequently miss the break lines along smaller stream courses that are critical to simulating the degree of surface water/groundwater interaction.

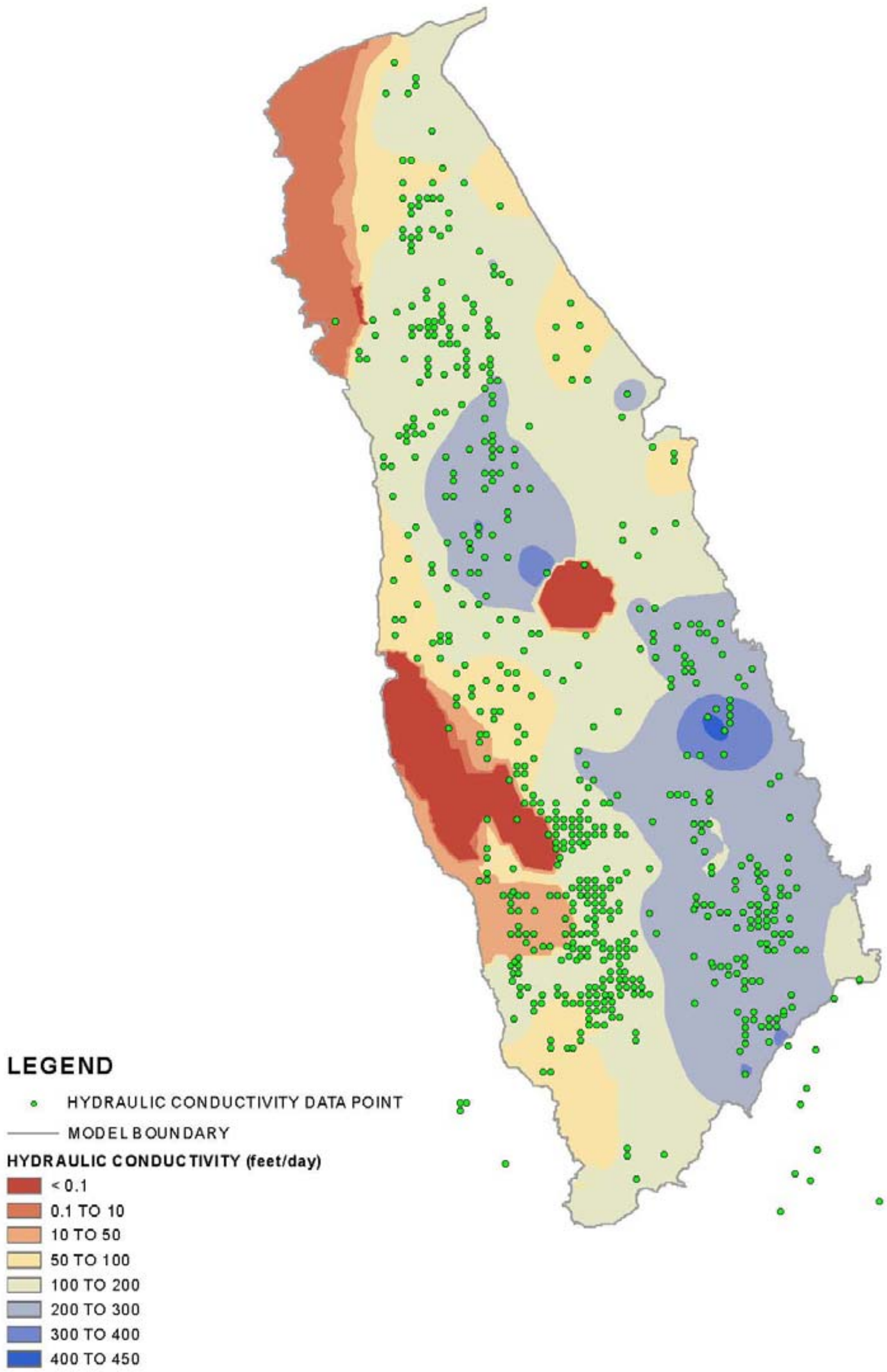

FIGURE B-5
SACFEM Hydraulic Conductivity Distribution

The process used here was to compile topographic data that were prepared considering topographic features, such as that provided on USGS topographic maps. Individual streambed elevations were augmented with stream gage elevation data, where available. A GIS-based algorithm was then developed to intersect the stream stage data with the nodes of the groundwater model grid, to ensure that stream stage elevations decline from the headwaters of the streams to the confluence with downstream rivers.

Because the SACFEM model uses a head-dependent stream boundary condition, and does not explicitly simulate stream routing and instream flows, the stream stages were assumed to remain constant throughout the simulation period. It is assumed that the effects of surface streams on the underlying groundwater system are more dependent on the frequency of wetting and drying conditions on the smaller tributary streams, and the average stream stages on the larger rivers, than they are on short-term transient stream stage fluctuations during storm events. This assumption was further evaluated by compiling groundwater elevation data from wells located near surface streams that are instrumented with automated recording pressure transducers, and comparing the observed trends in groundwater levels with the stage fluctuation in the nearby streams. Although this comparison was greatly limited by the availability of daily stream stage data on tributary streams, the available data suggest that the response of the groundwater system in the Sacramento Valley to short-term stream stage fluctuations is significantly attenuated. Measured fluctuations in groundwater levels do not show short-term responses associated with stage fluctuations, but instead show a more gradual rise over the winter and spring months, followed by a decline over the subsequent summer months. These data suggest that using average stage values might be adequate to replicate the surface water/groundwater interaction behavior that occurs within the Sacramento Valley. This assumption will be more fully evaluated during the transient calibration process described below.

4.0 Model Calibration

This section describes the approach used to calibrate the SACFEM numerical modeling tool of the Sacramento Valley as well as the results of the calibration process.

4.1 Calibration Approach

The approach taken to calibrate the SACFEM model was to first perform a steady-state calibration to hydrologic conditions from an average water year, followed by performing a transient calibration to data from a historical hydrologic period.

4.1.1 Steady-state Calibration

During the development of the SACFEM model, a detailed transient agricultural water budget was quantified on a monthly time step for the period extending from water years 1970 through 2003. The first step in the steady-state calibration process was to select a period of average hydrologic conditions such that the water budget components did not reflect a time of significant increase or decrease in groundwater storage within the model domain. The water budget components for this selected period were then averaged, and the model was calibrated to both average groundwater levels and average stream discharges that occur during the calibration period.

The calibration data set selected for this effort was calendar year 2000. Calendar year 2000 was selected because it is the most recent year where water budget information is available that was characterized by average hydrologic conditions. A calendar year instead of a water year was used to facilitate the development of average groundwater elevation calibration targets. The measured target groundwater-level data were obtained from the Department, and much of the data are collected in the spring and the fall. If a water year were used as the calibration data set, the cut-off between water years at the end of September would coincide with the midpoint of the fall sampling event. The result would be that when average groundwater elevation values were calculated, some of the measurements would be from October of the previous year and some would be from September of the subsequent year, which would introduce error in the data set, especially if the year types were different. Using a calendar year eliminates this potential for error. In addition to the observed average groundwater-level measurements during the calibration period, several other calibration targets were considered, as described below.

Steady-state Calibration Targets. Several quantitative and qualitative calibration targets were used in the calibration process. Following are calibration targets:

- Average year 2000 groundwater elevations (251 wells used as calibration targets)
- Areas of gaining and losing streams (approximate)
- Approximate water budget quantities (order of magnitude comparison as no precise estimates are available)

Water Budget Modification. During the calibration process, it was anticipated that some adjustment to the water budget components that were computed using the surface water budget methodology described above would be necessary to obtain an acceptable degree of calibration. An initial water budget and water-level comparison performed using the raw input data provided by the root zone model and surface water budgeting methodology suggested that the prescribed deep percolation rates in the northern (Red Bluff area) and southern (Davis/Woodland area) areas were too high. Deep percolation rates were reduced in these areas, resulting in a significant improvement in calibration residuals. To run the model in a transient mode, it was also necessary to make similar adjustments to the prescribed transient monthly deep percolation rates obtained from the surface water budget/root zone model. This was accomplished by computing the percent reduction in deep percolation that was required at each model node to obtain an acceptable steady-state calibration. It was then assumed that these same nodal reduction percentages were applicable to the monthly deep percolation estimates throughout the transient simulation period. These reduction percentages were then applied to all monthly deep percolation values applied during the transient calibration process described below.

Steady-state Calibration Results to Year 2000 Groundwater Elevations. A way to graphically measure the state of calibration using steady-state targets is to develop a scattergram that plots the simulated versus the measured groundwater elevation at each target calibration well. A plot of this type is shown on Figure B-6. A perfect fit between simulated and observed groundwater elevations would plot as a 45-degree line (slope = +1.0, Y-intercept = 0). As shown on Figure B-6, the simulated heads generated by the SACFEM model show good agreement between simulated and observed groundwater levels. This implies that the model is providing accurate estimates of the steady-state groundwater elevations and flow directions that exist near the potential project sites evaluated under this conjunctive water management evaluation program.

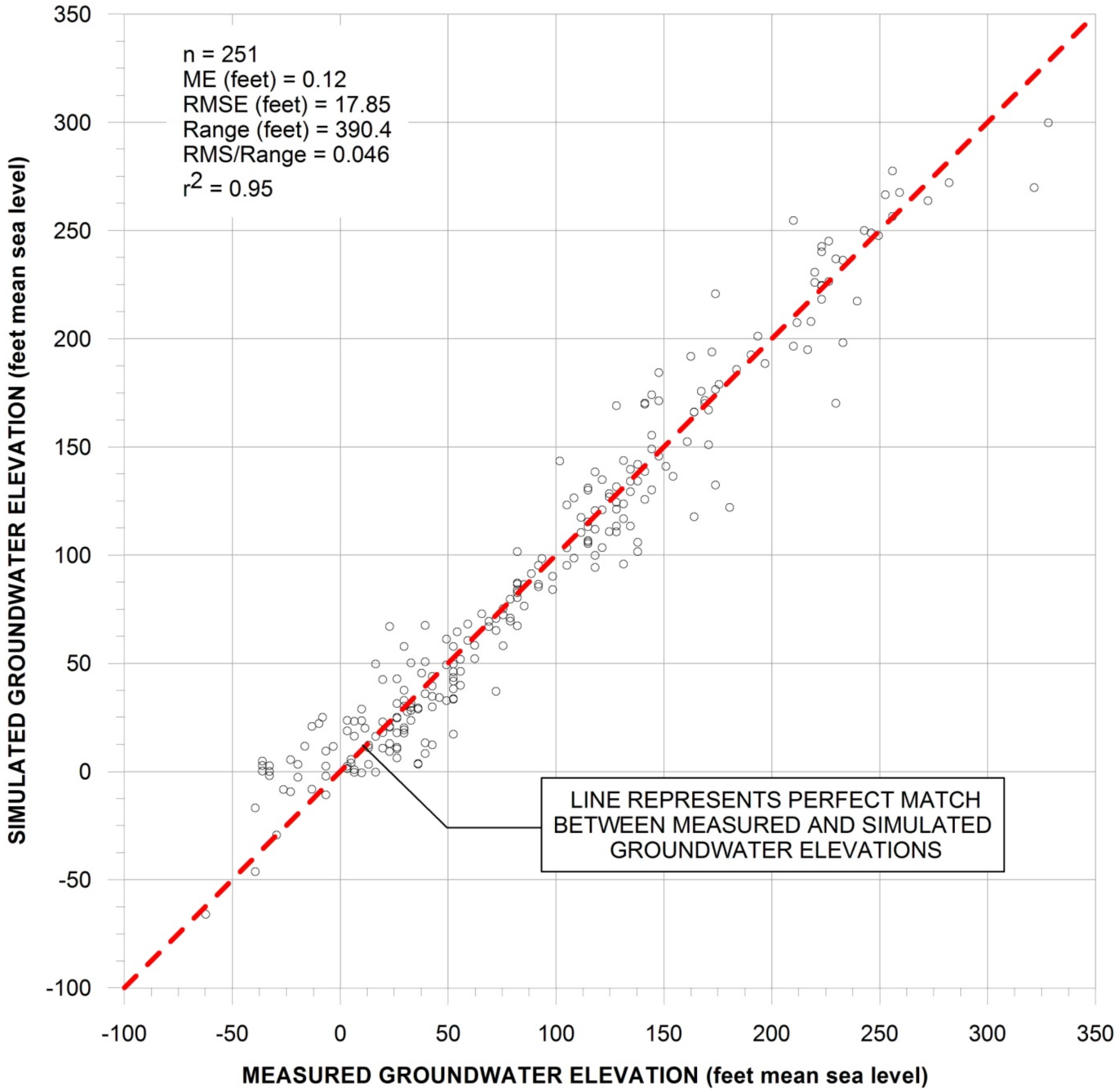

FIGURE B-6
SACFEM Calibration Scattergram

Another commonly used quantitative measure of calibration is the calculation of the root mean square (RMS) error (RMSE) divided by the range of observations. As a rule of thumb, a well-calibrated regional model will have an RMS/Range of less than 10 percent, and a well-calibrated local-scale mode will have an RMS/Range of less than 5 percent. The RMS/Range of the steady-state calibration presented here is 4.6 percent, well below the 10 percent criteria.

4.1.2 Calibrations to Gaining and Losing Stream Segments

In the Sacramento Valley, a further qualitative calibration target is the identification of stream segments that are gaining flow through groundwater discharge versus losing flow to groundwater recharge. Although the exact stream reaches that gain or lose flow because of surface water/groundwater interaction are not fully delineated, and this relationship changes over time with fluctuating groundwater levels and stream stages, the general pattern observed in the valley is that the major trunk streams, such as the Sacramento, Feather, and American Rivers, tend to gain flow, especially in their lower reaches; and the smaller upper tributaries near the basin margin tend to lose flow to the groundwater system. The stream reaches predicted by the model to gain or lose flow to the groundwater aquifer are shown on Figure B-7. The pattern predicted by the calibrated groundwater flow model is reasonably consistent with the generally accepted pattern described above. The distribution shown on Figure B-7 should be considered an average condition, with greater stream lengths likely gaining groundwater during wet periods with higher groundwater levels, and greater stream lengths losing water to the aquifer system during dry periods with lower groundwater levels.

4.1.3 Calibration to Steady-state Water Budget

The magnitude of the water budget components derived from the steady-state calibration are summarized in Table B-1. Although exact comparative estimates are not available for most of these components, rough estimates are. For example, the year 2000 calibration simulation estimates a combined 2.5 million acre-feet of groundwater pumping within the model domain, which agrees reasonably well with the generally accepted value of between 2.5 and 3.0 million acre-feet of groundwater withdrawal in an average year. Similarly, although no independent estimates of the quantity of groundwater that discharges to the Sacramento River are available, the average simulated value of 975 cubic feet per second, which represents approximately 2 to 4 percent of mean annual flow measured at the Freeport Gage, is reasonable.

4.1.4 Transient Calibration

The next step in the calibration process was to perform a transient calibration to a historical hydrologic period. The hydrologic period chosen to perform the transient calibration was water years 1970 through 2003. The period 1970 though 2003 was used because it includes very wet periods such as the winter of 1983, as well as dry periods such as the 1976 to 1977 and 1988 through 1992 droughts. Using a climatic period of this type allows for assessment of model accuracy and the water budgeting process at replicating observed conditions during periods of extreme hydrologic conditions, as well as the more average conditions that persisted throughout the remainder of the calibration period.

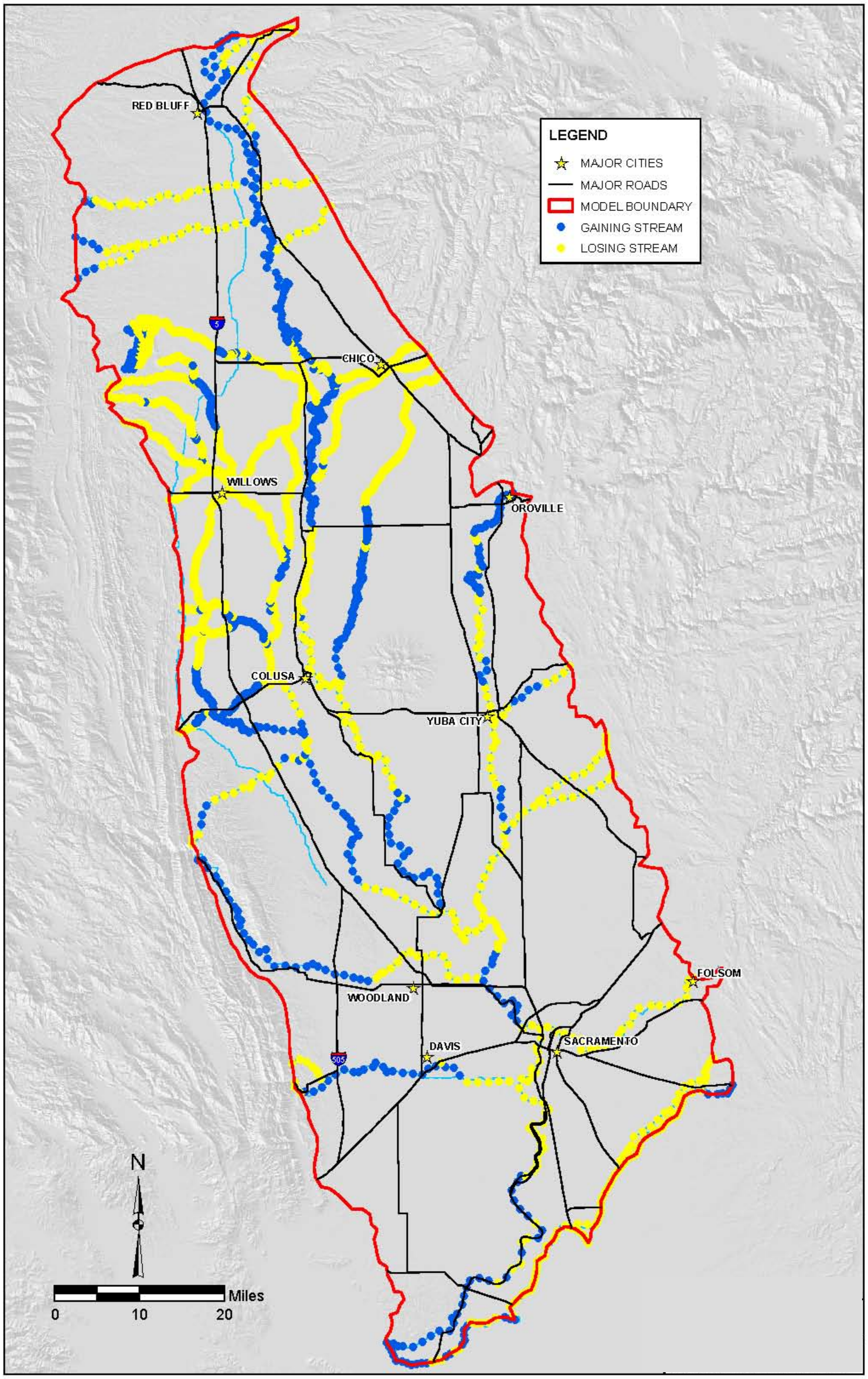

FIGURE B-7
Simulated Gaining and Losing Stream Reaches

TABLE B-1
Average Annual or Year 2000 SACFEM Water Budget Summary

Recharge	Acre-feet	Cubic Feet per Second
Recharge		
Deep Percolation of Precipitation	1,398,461	1,932
Deep Percolation of Applied Water	865,131	1,195
Mountain-front Recharge	495,507	684
Seepage from Streams to Groundwater	816,848	1,128
Total Recharge	**3,575,947**	**4,939**
Discharge		
Agricultural Pumping	**2,417,506**	3,339
Urban Pumping	451,507	624
Groundwater Discharge to Streams	705,999	975
Total Discharge	**3,575,012**	**4,938**

Selection of Calibration Wells. The selection of transient groundwater elevation targets was performed by conducting several database queries on the database of historical groundwater monitoring data for the Sacramento Valley provided by the Department. The first query was to identify all wells with well construction information, and to eliminate all data records for wells with unknown construction. The next step was to summarize the number of data records that were associated with each of the remaining wells within the water years 1970 through 2003 period. Wells with a higher number of records were preferred in further evaluation steps. After the wells that had construction information and a relatively large number of records within the calibration window were identified, it was necessary to ensure that the final wells selected as target calibration wells provided a good geographic distribution throughout the model domain, both within individual layers and with depth. This step was performed using a visual identification method as opposed to an automated query. The overall result of this process was that 65 monitoring wells were identified that provided transient groundwater elevation targets over the calibration period. The locations of the calibration wells within each model layer are shown on Figure B-8.

Transient Calibration Results. The main parameters that were adjusted during the transient calibration process were the distribution of the magnitude of the deep percolation of precipitation and applied water and the aquifer storage properties. After adjustment during each calibration simulation, the resulting quantities of deep percolation were reviewed in conjunction with the land use and crop type of each area to ensure that the assumed values were consistent with typical agricultural practices.

The results of the transient calibration process were evaluated using two methods. The first was to develop a scattergram, similar to that used for the steady-state calibration that compares the simulated and observed groundwater levels for all target water level observations throughout the transient calibration period.

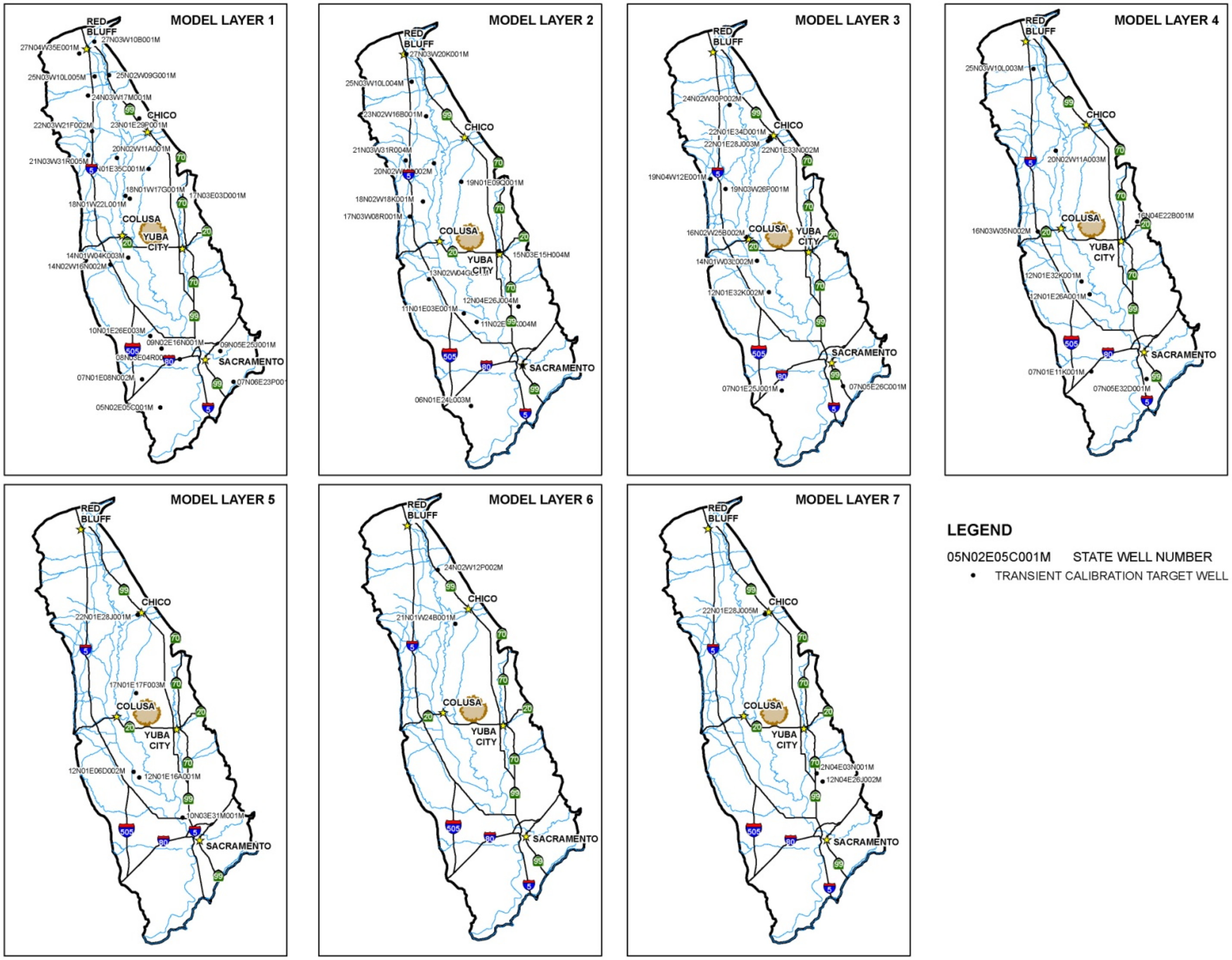

FIGURE B-8
Location of Transient Calibration Target Wells

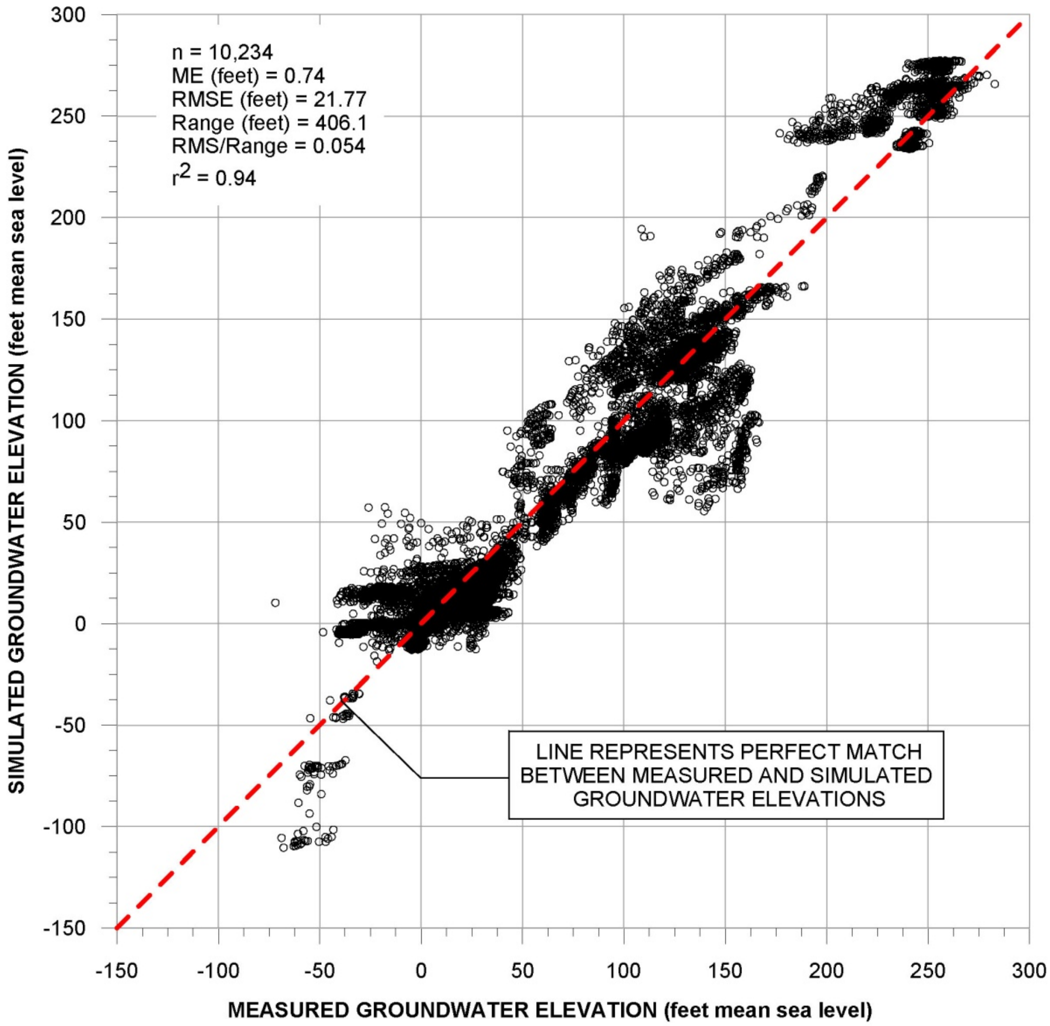

FIGURE B-9
Transient Calibration Scattergram

Figure B-9 shows the results of this comparison for all 10,234 water level measurements used in the transient calibration process. The statistical parameters associated with this comparison are also presented on Figure B-9. The r^2 goodness of fit between the simulated and observed values is 0.94, and the RMSE divided by the range of observations is just over 5 percent. Both of these parameters demonstrate that the model provides transient simulated groundwater elevations that closely match observed values across the valley and throughout the 34-year calibration period.

The other method used to evaluate the quality of the transient calibration was to compare the simulated hydrographs for each of the 65 target monitoring wells with the measured hydrograph data. These hydrograph comparisons are presented on Figure B-10 (located at the end of this technical memorandum). Although some significant deviations remain between simulated and observed data during certain periods at select locations, generally the SACFEM model does a good job of replicating both the absolute groundwater elevations and transient trends at most calibration monitoring wells.

5.0 Summary and Conclusions

A relatively high-resolution, three-dimensional numerical groundwater flow model of the Sacramento Valley Groundwater Basin has been developed to support the evaluation of conjunctive water management projects across the valley. Specifically, the model was developed to assess the transient effects of groundwater pumping on groundwater levels and to estimate changes in surface water/groundwater interaction.

The current finite-element groundwater flow model grid has a resolution on the order of 325 feet (100 meters) in areas where conjunctive water management projects are being considered and effects are being evaluated. The model has been constructed such that future project-specific grids can be developed, and the 34-year agricultural water budget can be projected onto the new grid using a semi-automated GIS-based tool. The vertical resolution of the model consists of seven model layers. The uppermost model layer was limited to 50 feet or less in thickness to allow assessment of impacts on streams as well as riparian habitat and wetlands. Model layers 2 though 5 were selected to represent typical groundwater production zones within the valley. Layers 6 and 7 were developed to represent the Lower Tuscan Formation, where it exists, within the northeastern and central portions of the valley.

The surface water budget, including agricultural pumping and deep percolation of precipitation and applied water was developed using a GIS-based analysis that considers 2005 land use, crop types, water source, seniority of water rights, and availability of surface water on a monthly time step. These deep percolation fluxes and agricultural pumping fluxes are independently computed for each element in the model. The fluxes associated with mountain-front recharge and urban pumping were also simulated on a monthly time step. Surface stream stages were defined by using available data, including USGS topographic maps and stream gage elevations, and assumed to be constant throughout the course of the model simulations.

The SACFEM model was calibrated to both steady-state and transient groundwater elevation data sets. The calendar year 2000 water levels were used as the steady-state calibration targets, and groundwater elevations recorded during the hydrologic period from water years 1970 through 2003 were used as transient calibration targets. More qualitative calibration targets such as the magnitude of the water budget components and the pattern and magnitude of surface water/groundwater interaction were also considered.

The SACFEM model represents a valuable analytical tool to estimate the effects of groundwater pumping on both groundwater levels and changes in surface water/groundwater interaction within the Sacramento Valley.

6.0 Works Cited

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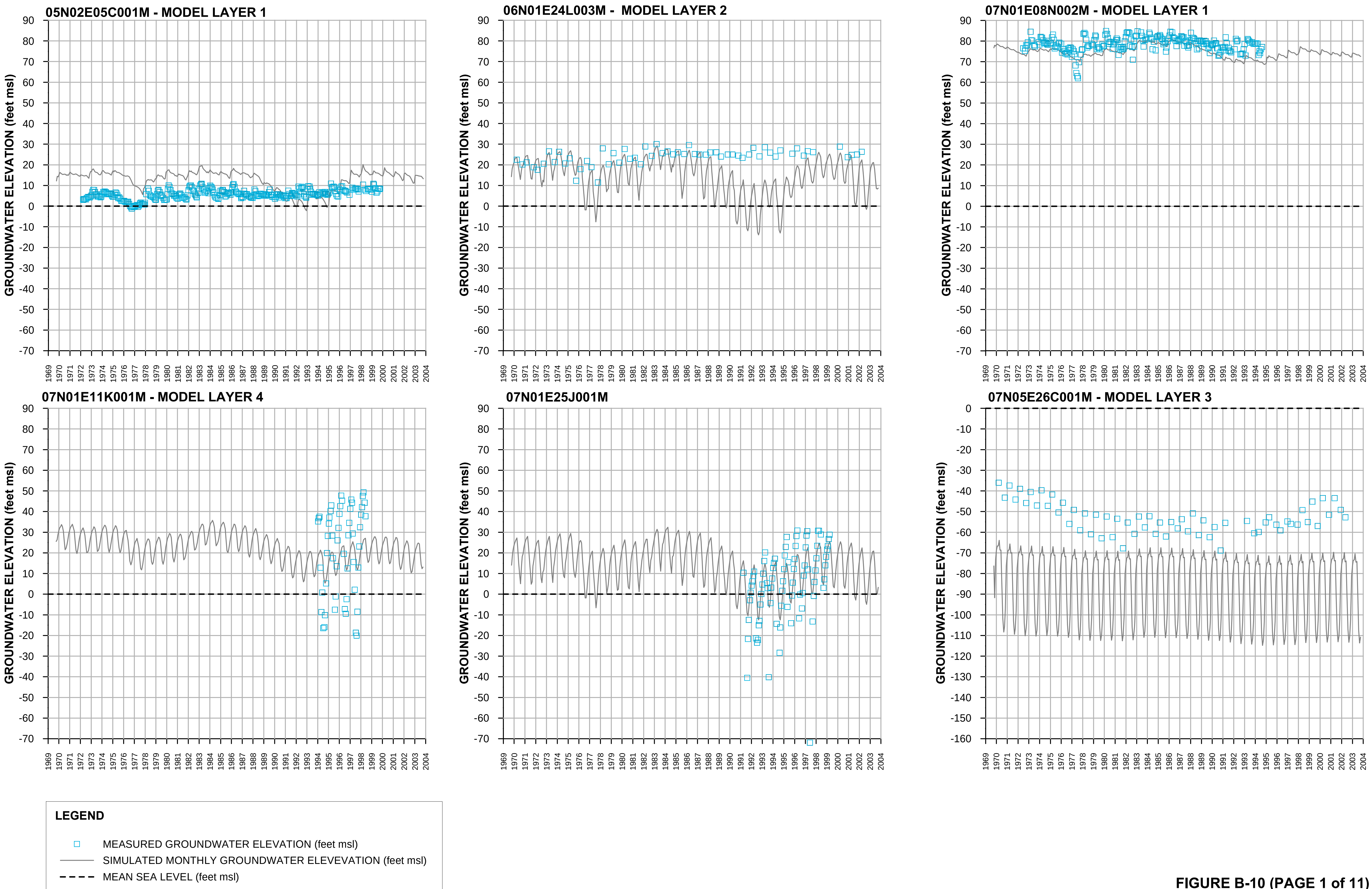
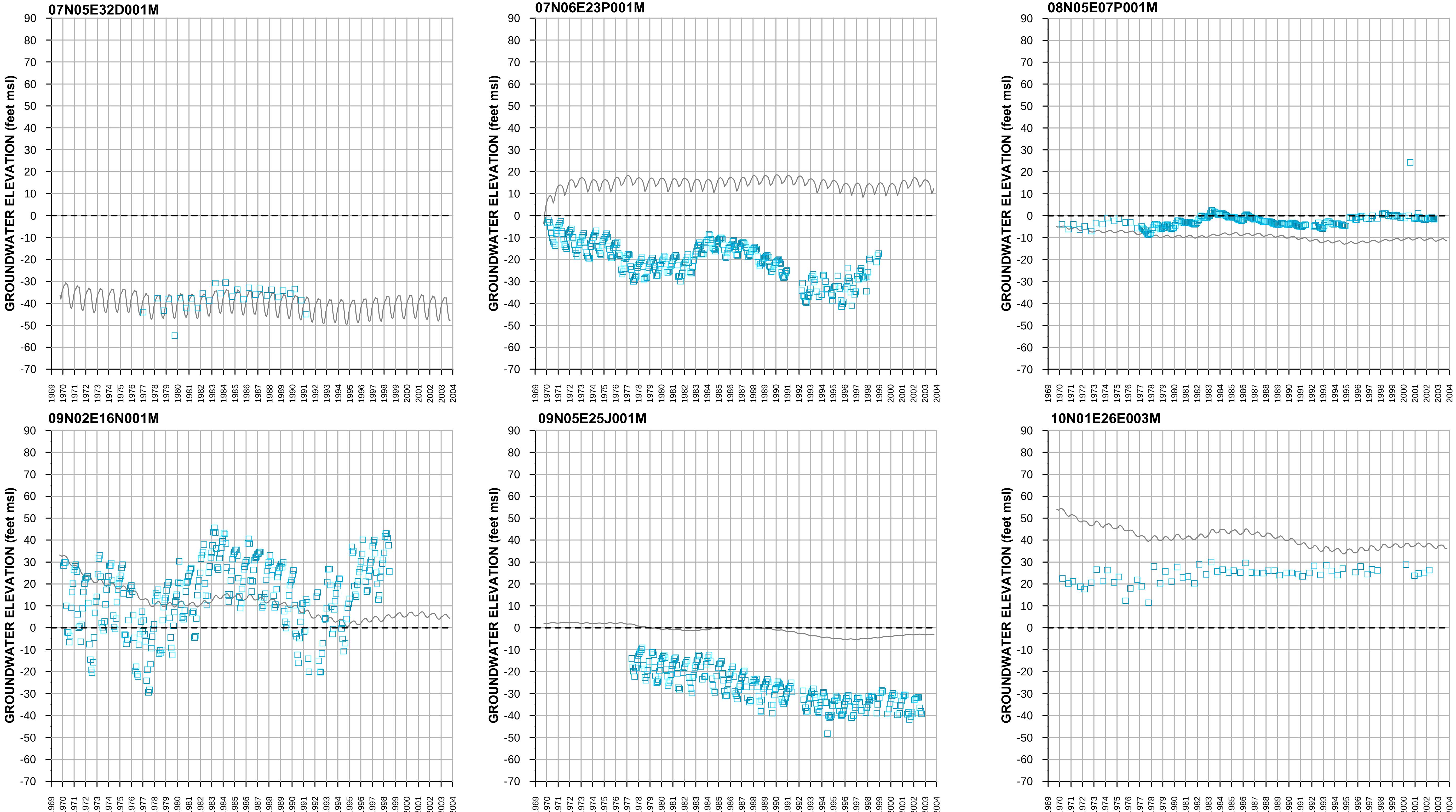


FIGURE B-10 (PAGE 1 of 11)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE SACFEM
GROUNDWATER FLOW MODEL
SACRAMENTO VALLEY GROUNDWATER BASIN

CH2MHILL

HYDROGRAPHS1.grf



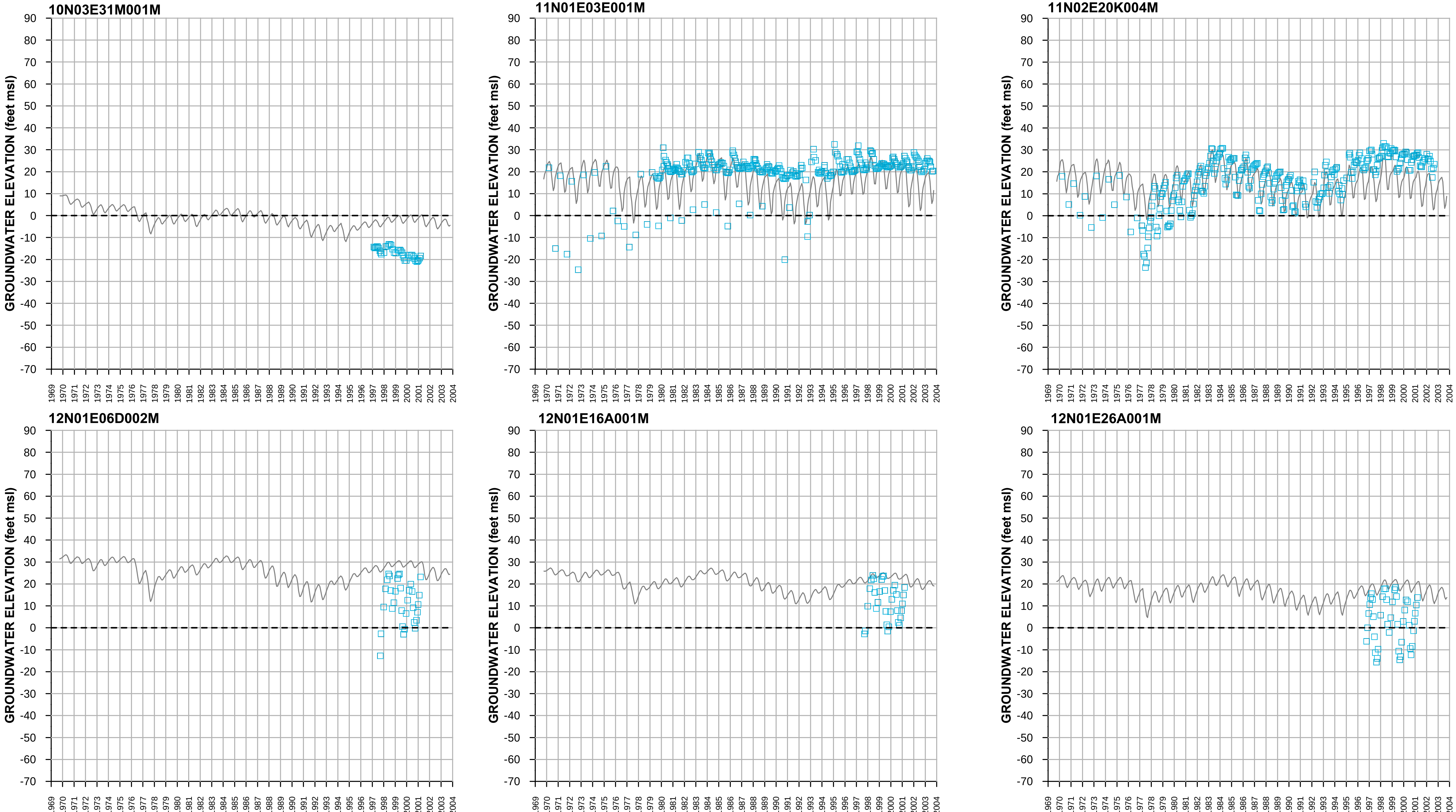
LEGEND

- MEASURED GROUNDWATER ELEVATION (feet msl)
- SIMULATED MONTHLY GROUNDWATER ELEVEVATION (feet msl)
- MEAN SEA LEVEL (feet msl)

FIGURE B-10 (PAGE 2 of 11)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE SACFEM
GROUNDWATER FLOW MODEL
SACRAMENTO VALLEY GROUNDWATER BASIN

CH2MHILL

HYDROGRAPHS2.grf



LEGEND

- MEASURED GROUNDWATER ELEVATION (feet msl)
- SIMULATED MONTHLY GROUNDWATER ELEVEVATION (feet msl)
- MEAN SEA LEVEL (feet msl)

FIGURE B-10 (PAGE 3 of 11)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE SACFEM
GROUNDWATER FLOW MODEL
SACRAMENTO VALLEY GROUNDWATER BASIN

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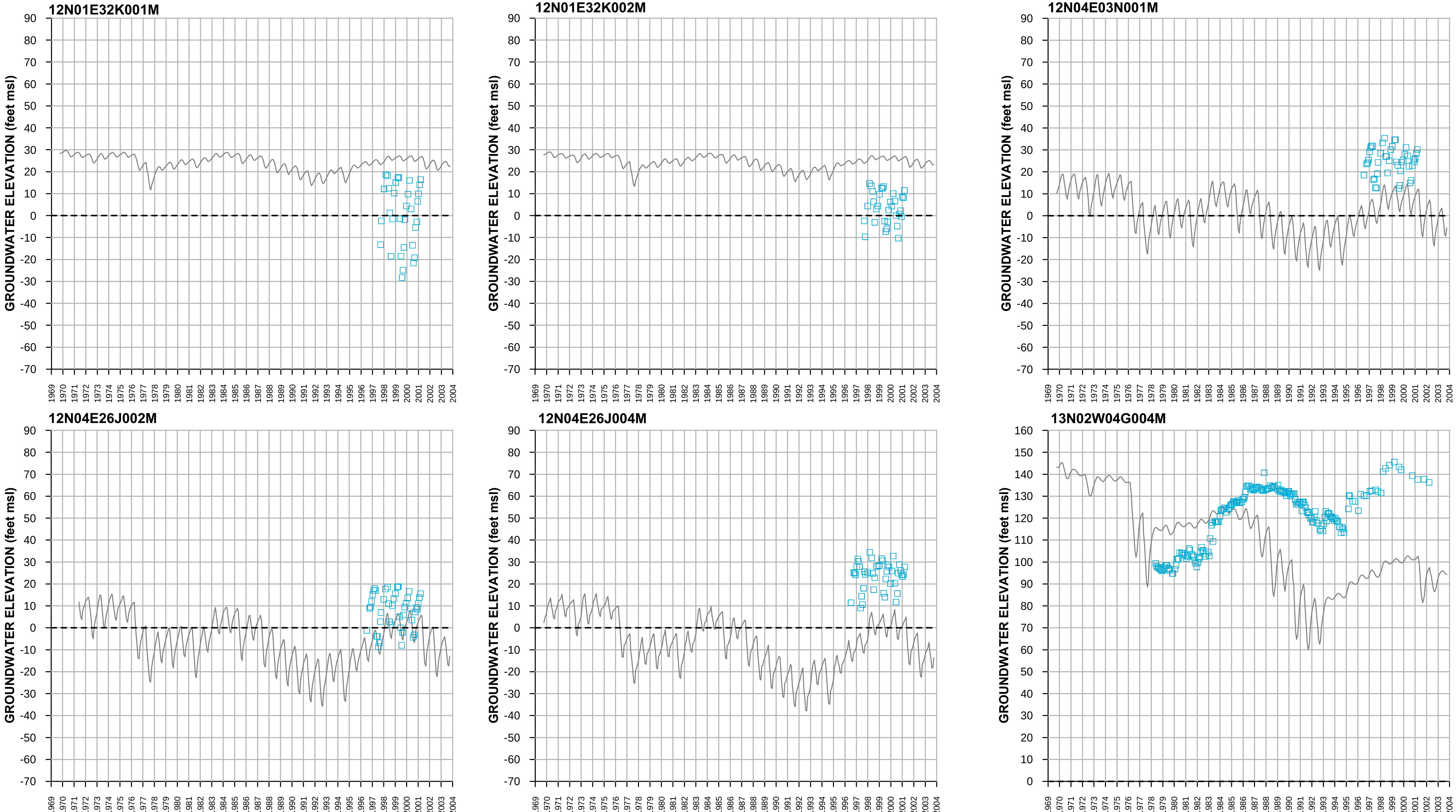

LEGEND

- MEASURED GROUNDWATER ELEVATION (feet msl)
- SIMULATED MONTHLY GROUNDWATER ELEVEVATION (feet msl)
- MEAN SEA LEVEL (feet msl)

FIGURE B-10 (PAGE 4 of 11)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE SACFEM
GROUNDWATER FLOW MODEL
SACRAMENTO VALLEY GROUNDWATER BASIN

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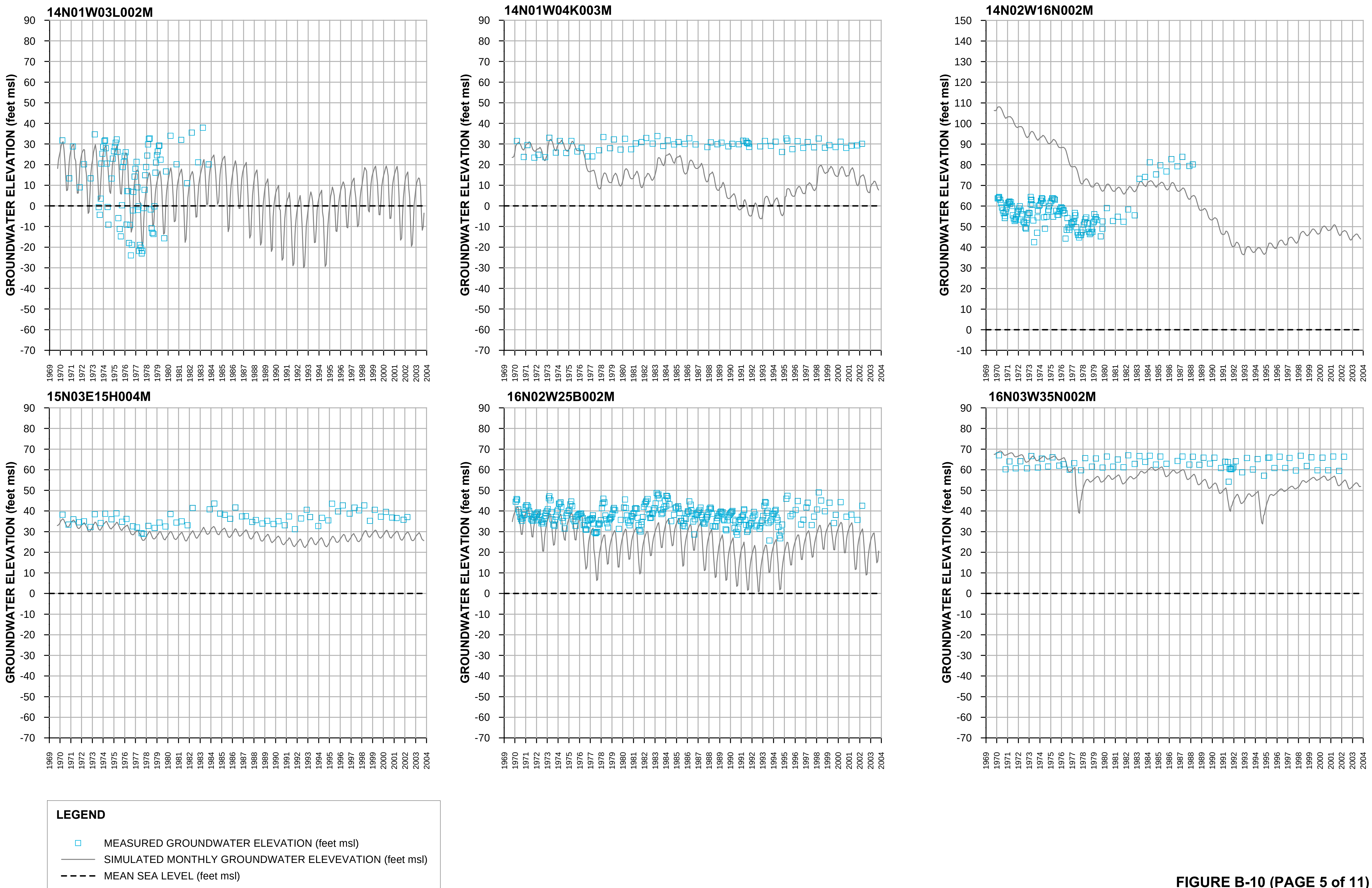

FIGURE B-10 (PAGE 5 of 11)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE SACFEM
GROUNDWATER FLOW MODEL
SACRAMENTO VALLEY GROUNDWATER BASIN

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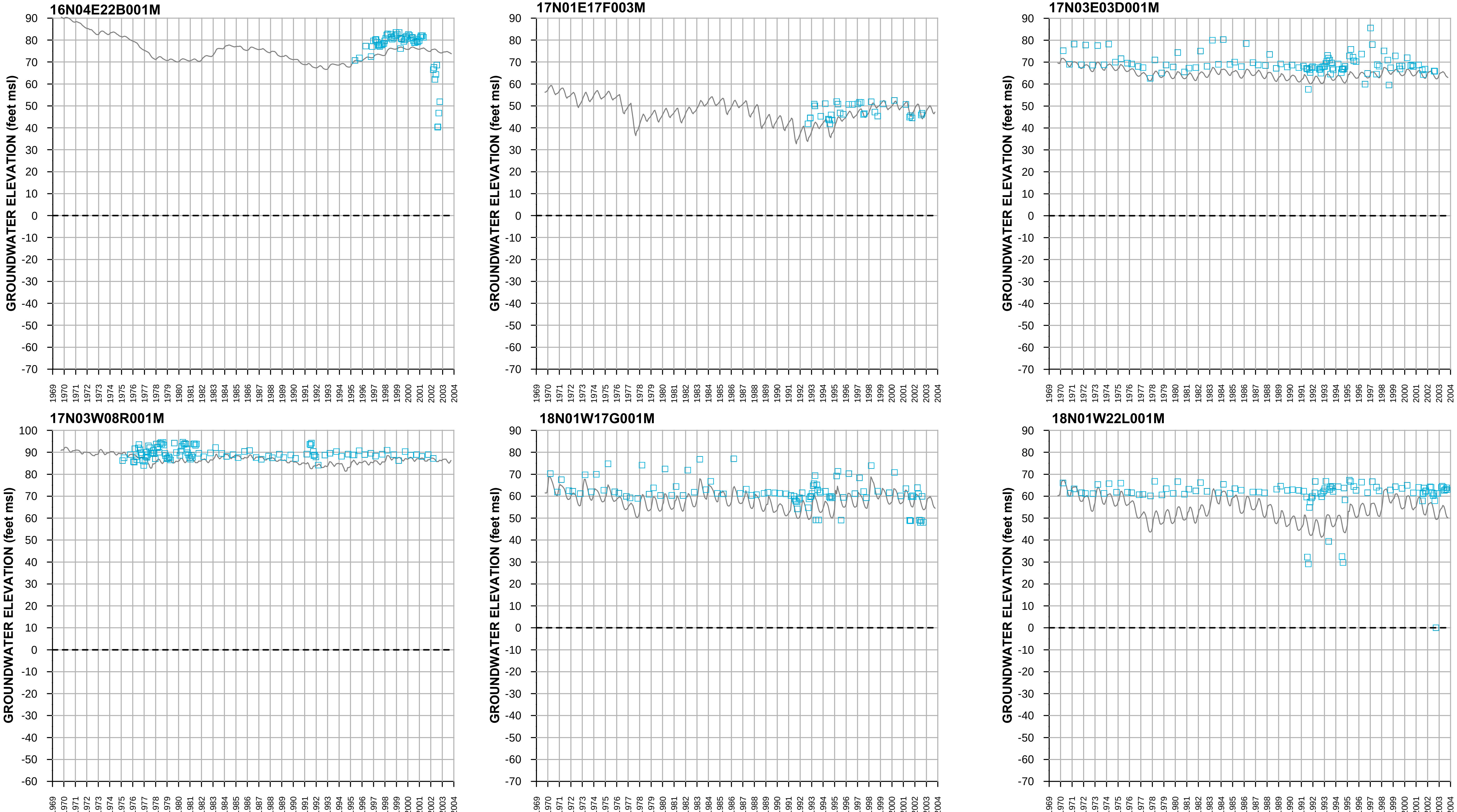
HYDROGRAPHS4.grf



LEGEND

- MEASURED GROUNDWATER ELEVATION (feet msl)
- SIMULATED MONTHLY GROUNDWATER ELEVEVATION (feet msl)
- MEAN SEA LEVEL (feet msl)

FIGURE B-10 (PAGE 6 of 11)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE SACFEM
GROUNDWATER FLOW MODEL
SACRAMENTO VALLEY GROUNDWATER BASIN

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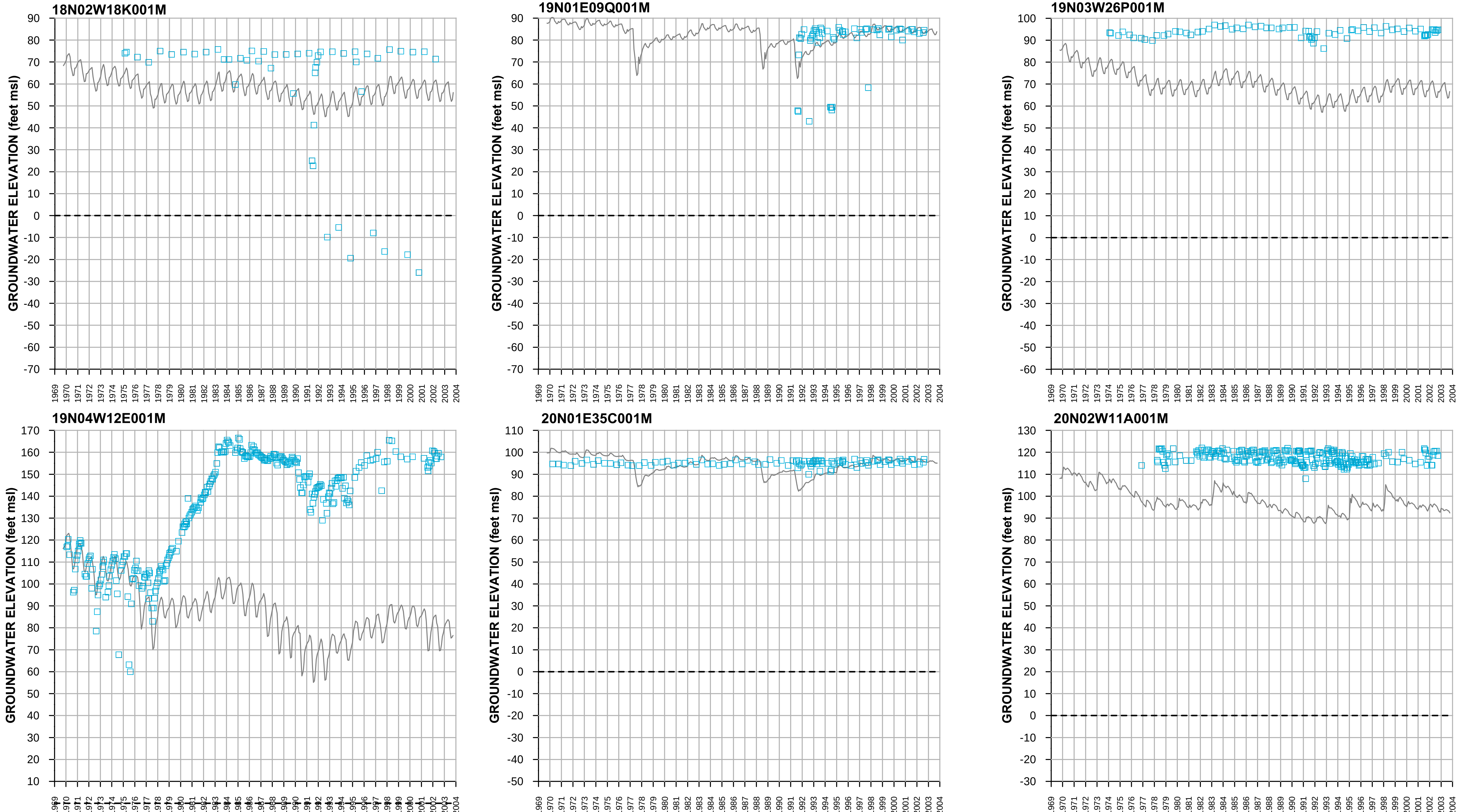
HYDROGRAPHS6.grf



LEGEND

□ MEASURED GROUNDWATER ELEVATION (feet msl)

SIMULATED MONTHLY GROUNDWATER ELEVEVATION (feet msl)

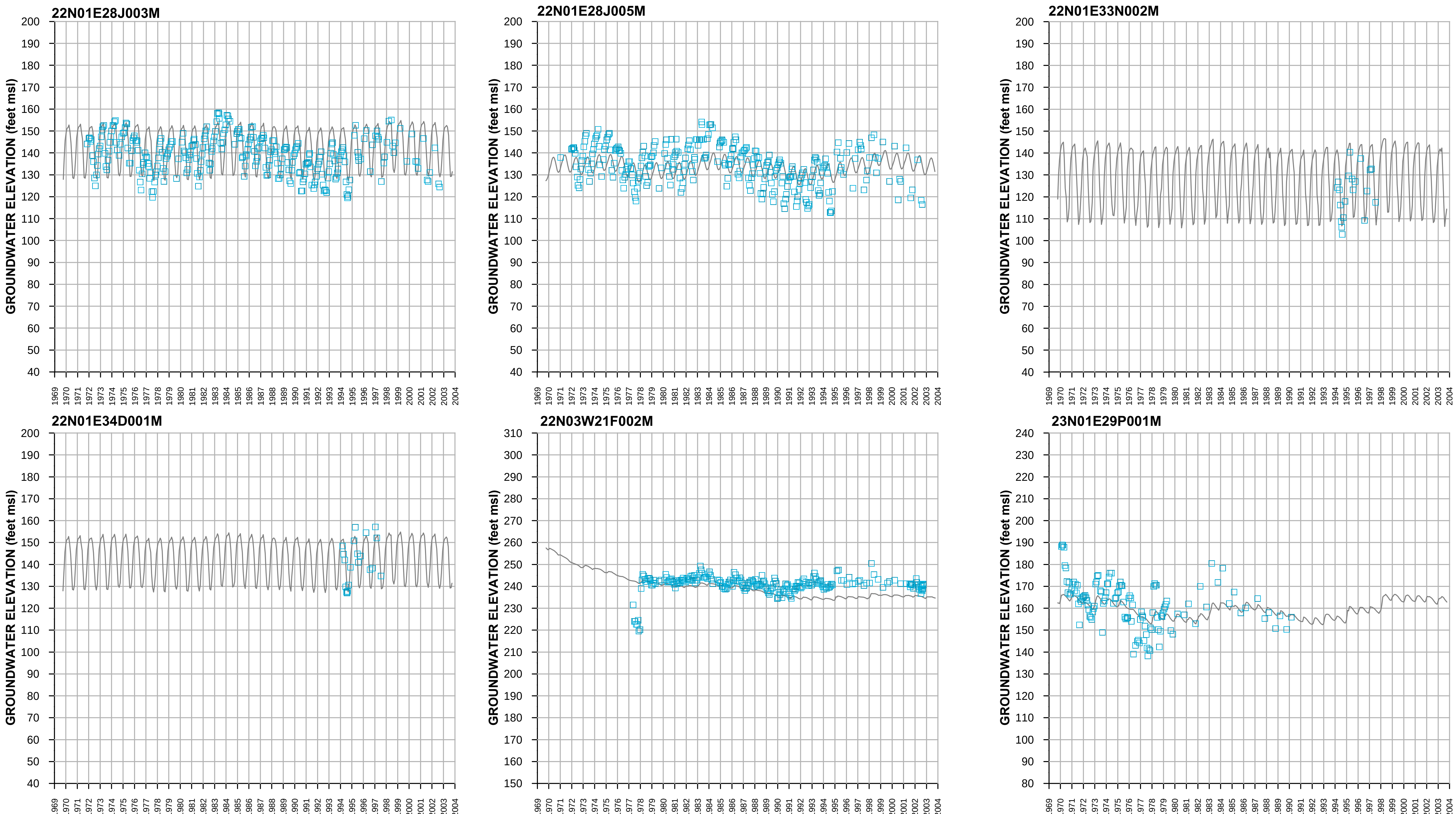
MEAN SEA LEVEL (feet msl)

FIGURE B-10 (PAGE 7 of 11)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE SACFEM
GROUNDWATER FLOW MODEL
SACRAMENTO VALLEY GROUNDWATER BASIN

CH2MHILL

HYDROGRAPHS7.grf

FIGURE B-10 (PAGE 8 of 11)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE SACFEM
GROUNDWATER FLOW MODEL
SACRAMENTO VALLEY GROUNDWATER BASIN



LEGEND

- MEASURED GROUNDWATER ELEVATION (feet msl)
- SIMULATED DAILY GROUNDWATER ELEVEVATION (feet msl)
- MEAN SEA LEVEL (feet msl)

FIGURE B-10 (PAGE 9 of 11)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE SACFEM
GROUNDWATER FLOW MODEL
SACRAMENTO VALLEY GROUNDWATER BASIN

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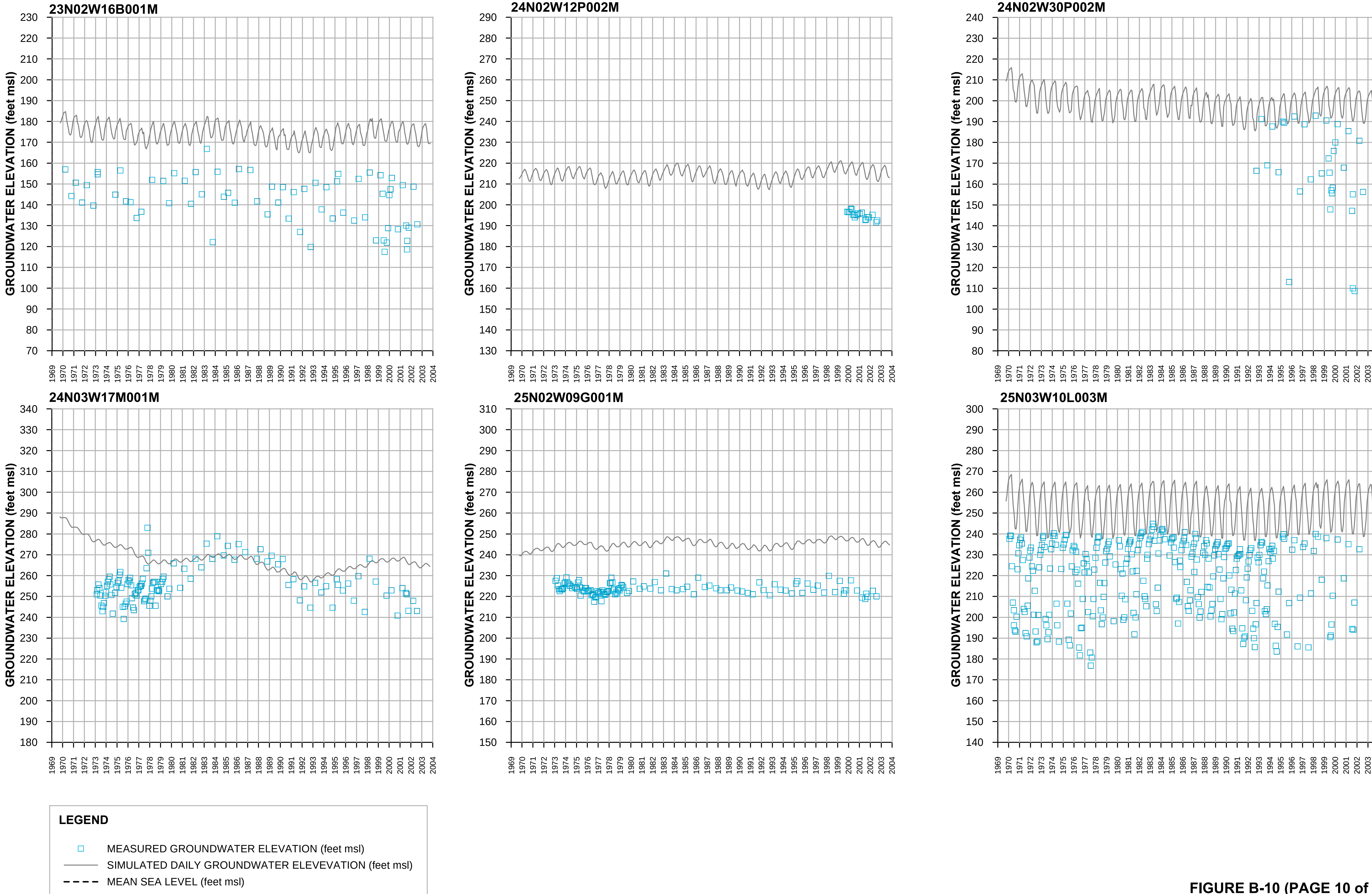

FIGURE B-10 (PAGE 10 of 11)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE SACFEM
GROUNDWATER FLOW MODEL
SACRAMENTO VALLEY GROUNDWATER BASIN

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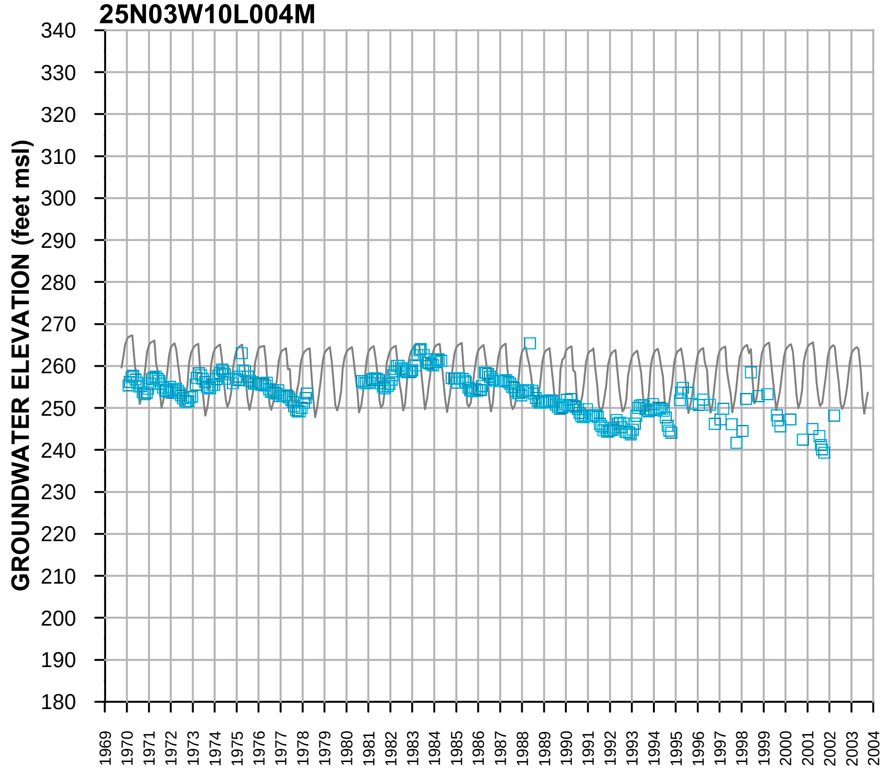

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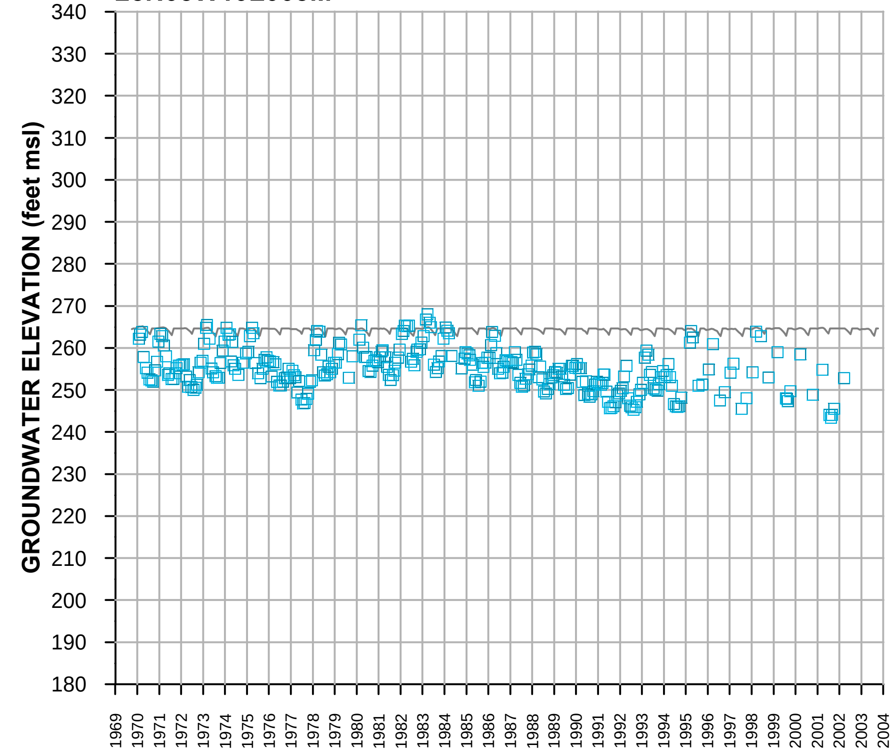

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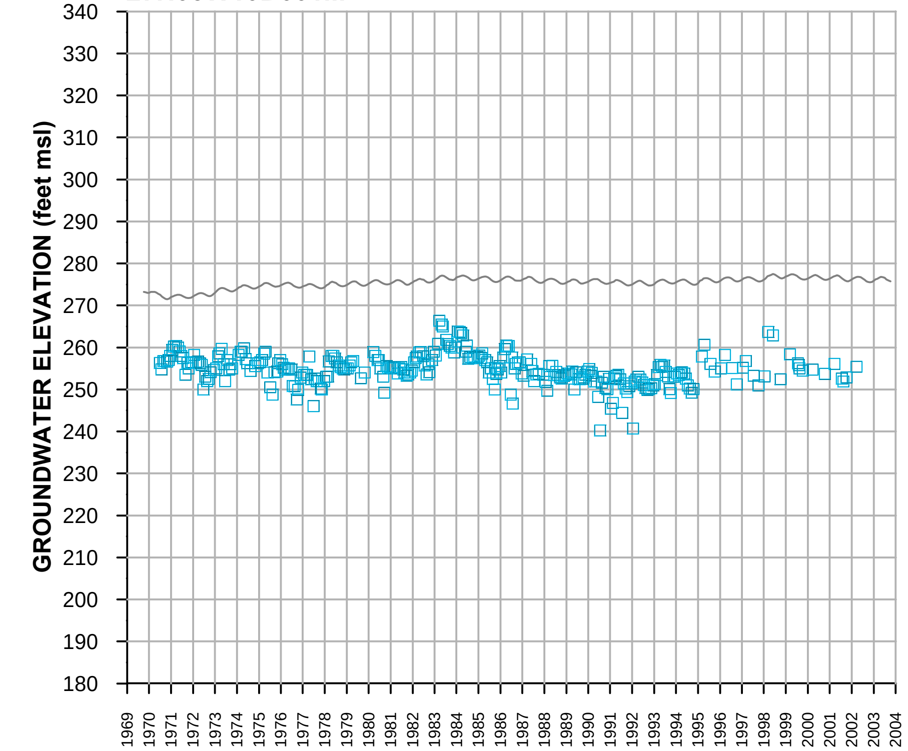

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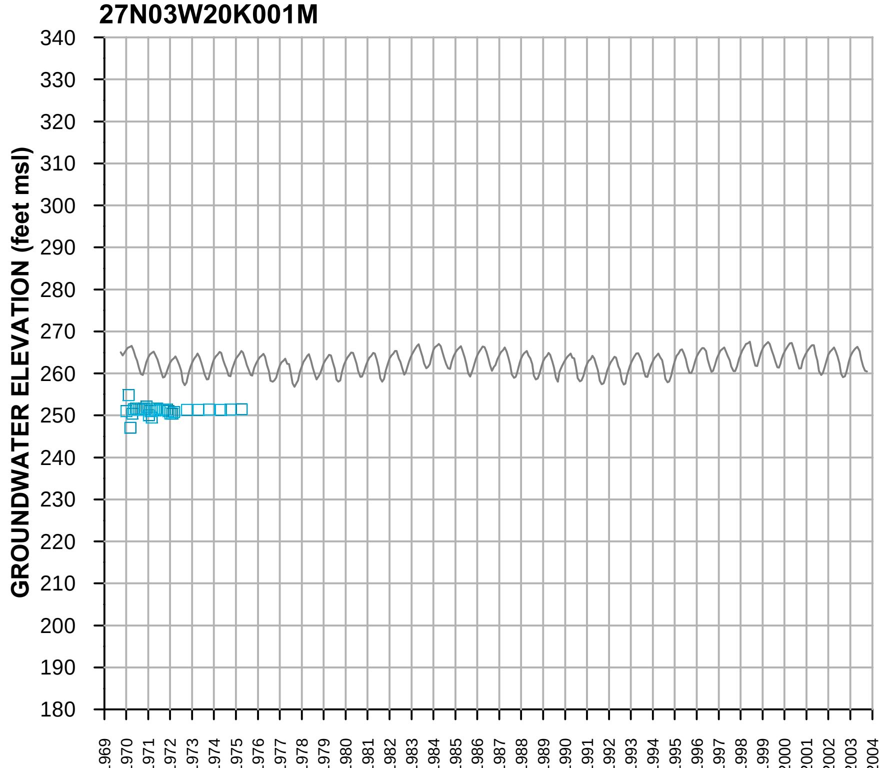

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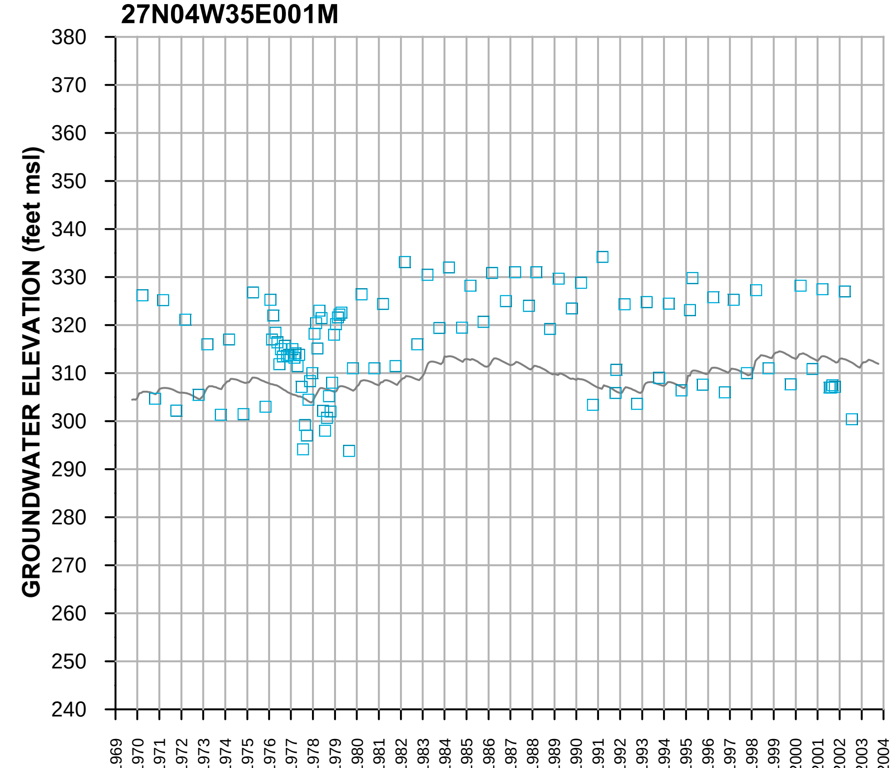

LEGEND

- MEASURED GROUNDWATER ELEVATION (feet msl)
- SIMULATED DAILY GROUNDWATER ELEVEVATION (feet msl)
- MEAN SEA LEVEL (feet msl)

FIGURE B-10 (PAGE 11 of 11)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE SACFEM
GROUNDWATER FLOW MODEL
SACRAMENTO VALLEY GROUNDWATER BASIN

CH2MHILL

HYDROGRAPHS11.grf