SECTION 3
Groundwater Flow Model Construction

3.1 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 SVGB. The current version of the program (4.10) 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 (more than 5,960 square miles in the SVGB) 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 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.

3.1.1 Numerical Assumptions

MicroFEM, as applied to the development of SACFEM2013, is conceptualized mathematically into a single-density subsurface groundwater flow regime. The subsurface flow regime includes the hydraulic properties that control groundwater movement and rates. All model layers are treated as vertically integrated, leaky-confined layers to facilitate accurate simulation of the 3D groundwater flow conditions. The minimum inputs required by MicroFEM to execute a simulation for a given model grid include transmissivity, vertical resistance, and boundary conditions. SACFEM2013 is simulated under confined conditions in all model layers; therefore, the user-defined transmissivity values do not vary during the model simulation.

3.1.2 Scientific Bases

The theory and numerical techniques that are incorporated into MicroFEM have been scientifically tested. The governing equations for saturated subsurface flow are well established and have been solved by several modeling codes over the past few decades on a wide range of field problems. Thus, the scientific bases of the theory and the numerical techniques for solving these equations have been well established. MicroFEM has been developed using strict quality assurance/quality control guidelines and with various levels of testing, from simple analytical solutions to complex field problems.

3.1.3 Data Formats

MicroFEM input and output files use American Standard Code for Information Interchange (ASCII) data formats and can be read and edited outside the program by a text editor.

3.1.4 Limitations

Mathematical models can only approximate processes of physical systems. Models are inherently inexact because the mathematical description of the physical system is imperfect and the understanding of interrelated physical processes is incomplete. CH2M HILL incorporated as many details of the physical system into the numerical model as possible. SACFEM2013 is a powerful tool that, when used carefully, can provide useful insight into processes of the physical system. Section 4.3 discusses potential sources of input and output error.

3.2 Model Construction

The mathematical model design is the result of translating the CSM into a form that is suitable for numerical modeling. The following steps were included in the development of the mathematical model design:

1. Establishing study area boundaries (that is, model domain) and developing a model grid
2. Spatially distributing land surface elevation values
3. Spatially distributing subsurface hydraulic parameter values
4. Selecting a time discretization approach appropriate for evaluating the field problem and fulfilling the modeling objectives
5. Establishing boundary conditions for flow (that is, water budget terms through time)

The following subsections describe the results of these design steps.

3.2.1 Model Domain

In the real world, space is continuous, but a numerical model must use discrete space to represent the hydrologic system. The simplest way to discretize space is to subdivide the study area into many subregions (that is, model elements) of variable size. This was the approach taken for development of the SACFEM2013 grid.

3.2.1.1 Areal Characteristics of Model Grid

The current version of the SACFEM2013 grid consists of 153,812 nodes and 306,813 elements (see Figure 6). The current grid was configured to support evaluation of potential conjunctive water management projects associated with the Long-Term Water Transfer Program; however, SACFEM2013 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 current grid varies from as large as approximately 3,300 feet (1,000 meters) near the model boundary and in areas where long-term water transfer projects are not being evaluated, to as small as 410 feet (125 meters) in areas where long-term water transfer groundwater production is being evaluated. Nodal spacing of approximately 1,640 feet (500 meters) is included along streams and flood bypasses included in SACFEM2013. 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 SVGB.

Note: The horizontal datum for SACFEM2013 is Universal Transverse Mercator, North American Datum of 1983, Zone 10 North, meters. The vertical datum for SACFEM2013 is North American Vertical Datum of 1988, meters.

3.2.1.2 Vertical Characteristics of Model Grid

As previously discussed, MicroFEM uses the user-defined aquifer transmissivity when executing calculations under confined conditions. When constructing the SACFEM2013 model, aquifer transmissivity was divided into the two components: saturated aquifer thickness and horizontal hydraulic conductivity (transmissivity is equal to saturated thickness multiplied by horizontal hydraulic conductivity). The following section describes the conceptualization of the saturated aquifer thickness.

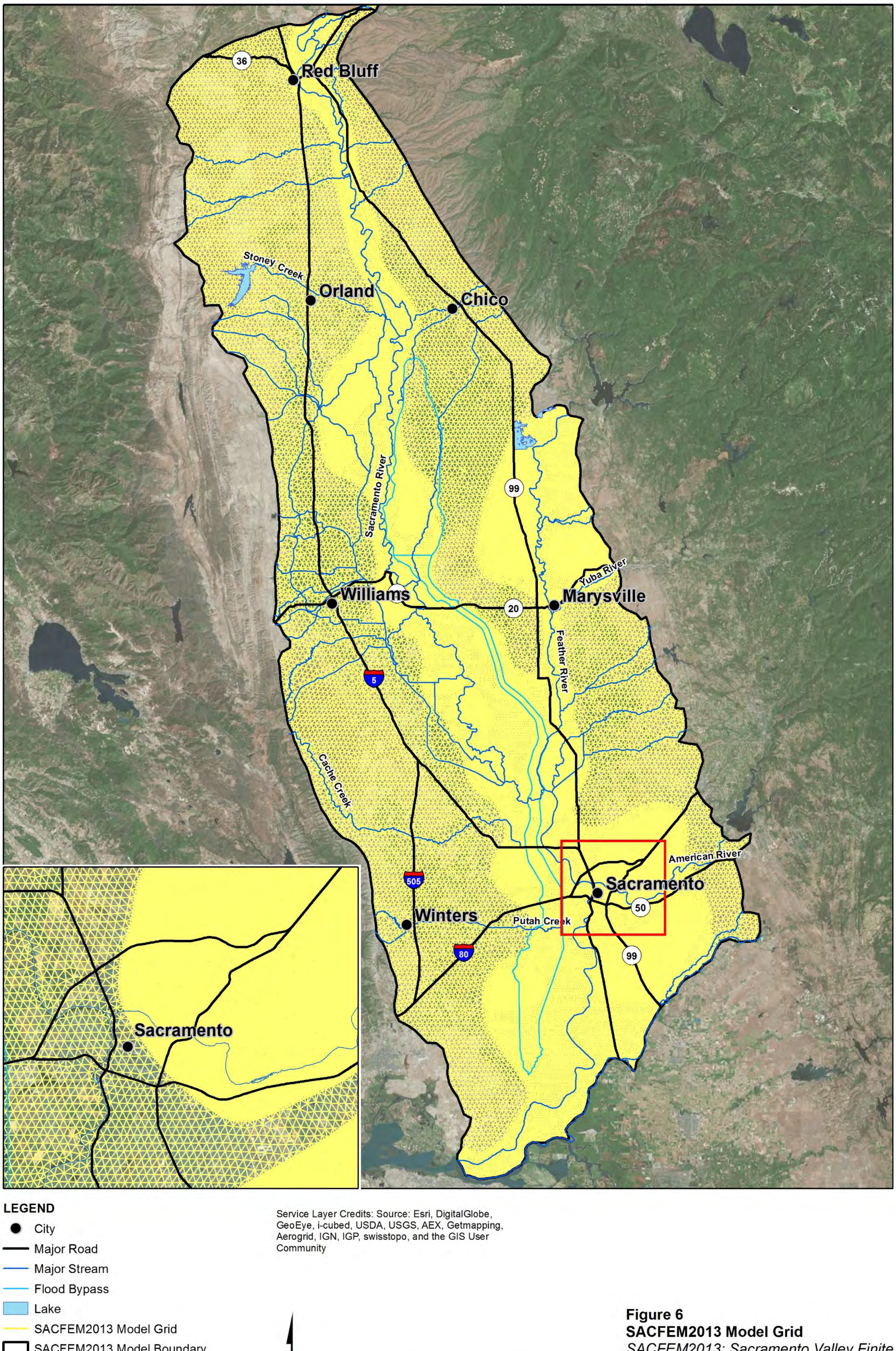

Figure 6
SACFEM2013 Model Grid
SACFEM2013: Sacramento Valley Finite Element Groundwater Flow Model
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The total model thickness is defined by the thickness of the freshwater aquifer (less than 3,000 micromhos per centimeter), as defined by Berkstresser (1973) and subsequently refined in the northern portion of the Valley by DWR (2002, 2005). For the southern portion of the model area, elevation contour lines of the base of fresh water, defined by Berkstresser data, along with information from boring locations (point measurements of the elevation of the base of fresh water) were digitized and used to generate a 3D 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 DWR 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 SVGB (see Figure 7).

Total Aquifer Thickness. Because SACFEM 2013 is simulated under confined conditions, the uppermost boundary of SACFEM2013 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. Average calendar year 2000 groundwater elevation measurements were obtained from the DWR 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, 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 saturated aquifer thickness across the model domain (see Figure 8).

Model Layer Thickness. The strategy used to develop the overall layering of the SACFEM2013 model was to develop a tool that provides a sufficient number of layers to assess the effects of groundwater pumping on shallow features such as wetlands and streams. The model also was developed 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. Additionally, to facilitate investigation of potential future conjunctive water management projects using the Lower Tuscan aquifer, the layering strategy also provided for two layers explicitly representing this deep aquifer system.

Layer 1 of the SACFEM2013 model was assigned a maximum thickness of approximately 65 feet (20 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 SVGB. The thicknesses of Layers 2 through 4 each represent approximately 10 percent of the total aquifer thickness (1 to 107 meters, 3 to 350 feet), and the thickness of Layer 5 represents approximately 15 percent of the total aquifer thickness on average (1 to 193 meters, 3 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 (Figure 9). 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 represent this condition in the model, Layer 6 was assigned a thickness of between 250 to 360 feet (75 to 110 meters) in the central portion of the northern SVGB. The total range in Layer 6 thickness is approximately 3 to 580 feet (1 to 177 meters). The remaining Lower Tuscan thickness not apportioned to Layer 6 was 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 represents 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 8, and cross sections illustrating SACFEM2013 model layers are presented on Figures 10 and 11 (these oversized figures are presented at the end of this report).

3.2.2 Subsurface Hydraulic Parameters

The hydraulic parameters in the SACFEM2013 were initially assigned using available and relevant field data from previous investigations. Subsurface hydraulic properties required by MicroFEM include the horizontal hydraulic conductivity (Kh) and the vertical resistance.

3.2.2.1 Horizontal Hydraulic Conductivity

The distribution of aquifer properties across the SVGB 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 DWR 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 DWR 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 operating 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 gpm 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.

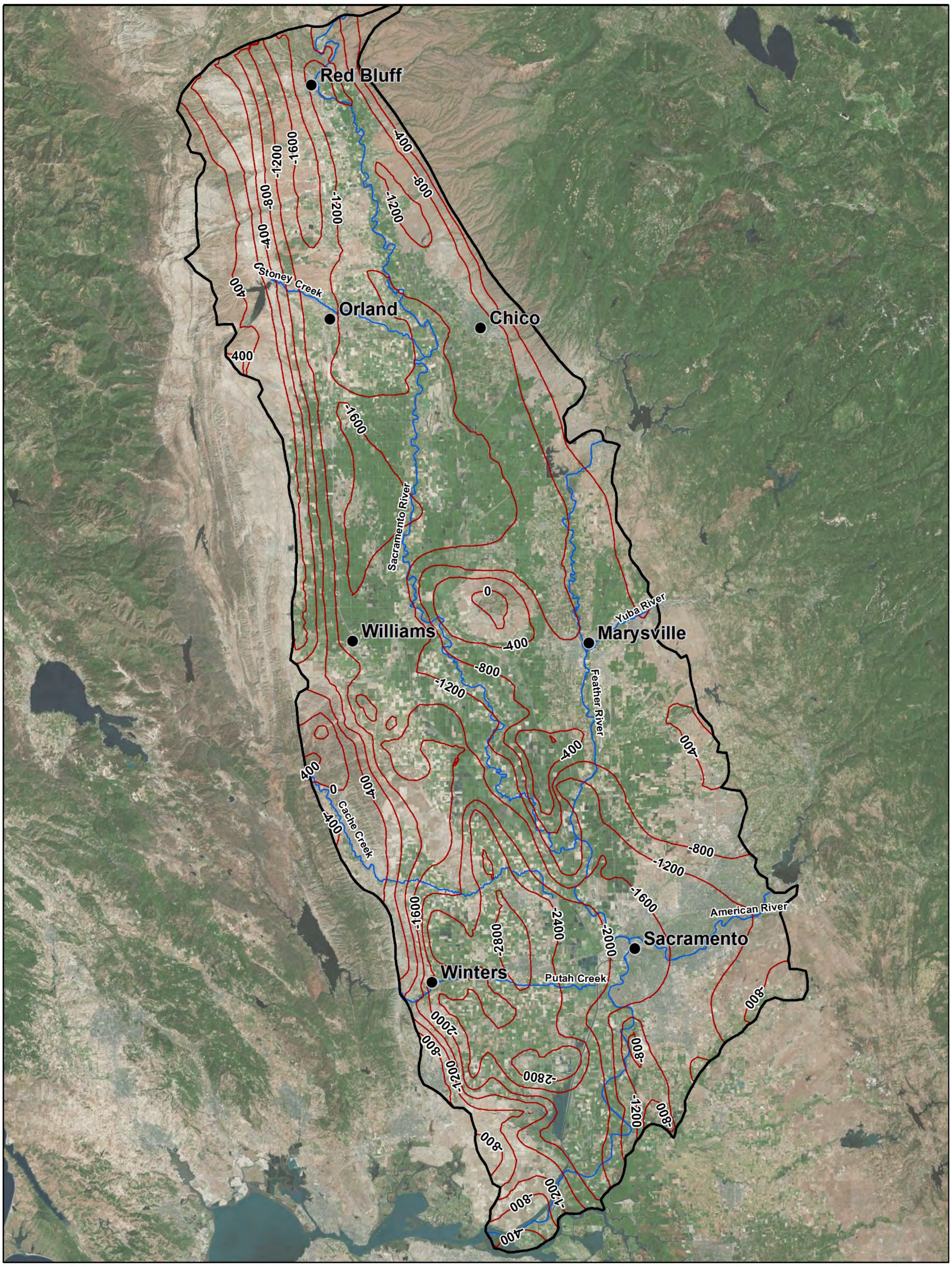
After the data set for consideration was finalized, the reported specific capacity data for each well were used to estimate an aquifer transmissivity for that location. The relationship used to estimate aquifer transmissivity was the following form of a simplified version of the Jacob non-equilibrium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

$$S_c = \frac{T}{2000} \qquad (1)$$

Where:

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

T = aquifer transmissivity (gallons per day per foot)



LEGEND

- ● City
- Major Stream
- SACFEM2013 Model Boundary
- Simulated Base of Fresh Groundwater (feet NAVD88)

Note:
NAVD88 = North American Vertical Datum of 1988

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

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Figure 7
Base of Fresh Groundwater
SACFEM2013: Sacramento Valley Finite Element Groundwater Flow Model
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LEGEND

- City
- Major Stream
- SACFEM2013 Model Boundary
- Contour of Equal Saturated Aquifer Thickness (feet)

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

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Figure 8
Total Saturated Aquifer Thickness
SACFEM2013: Sacramento Valley Finite Element Groundwater Flow Model
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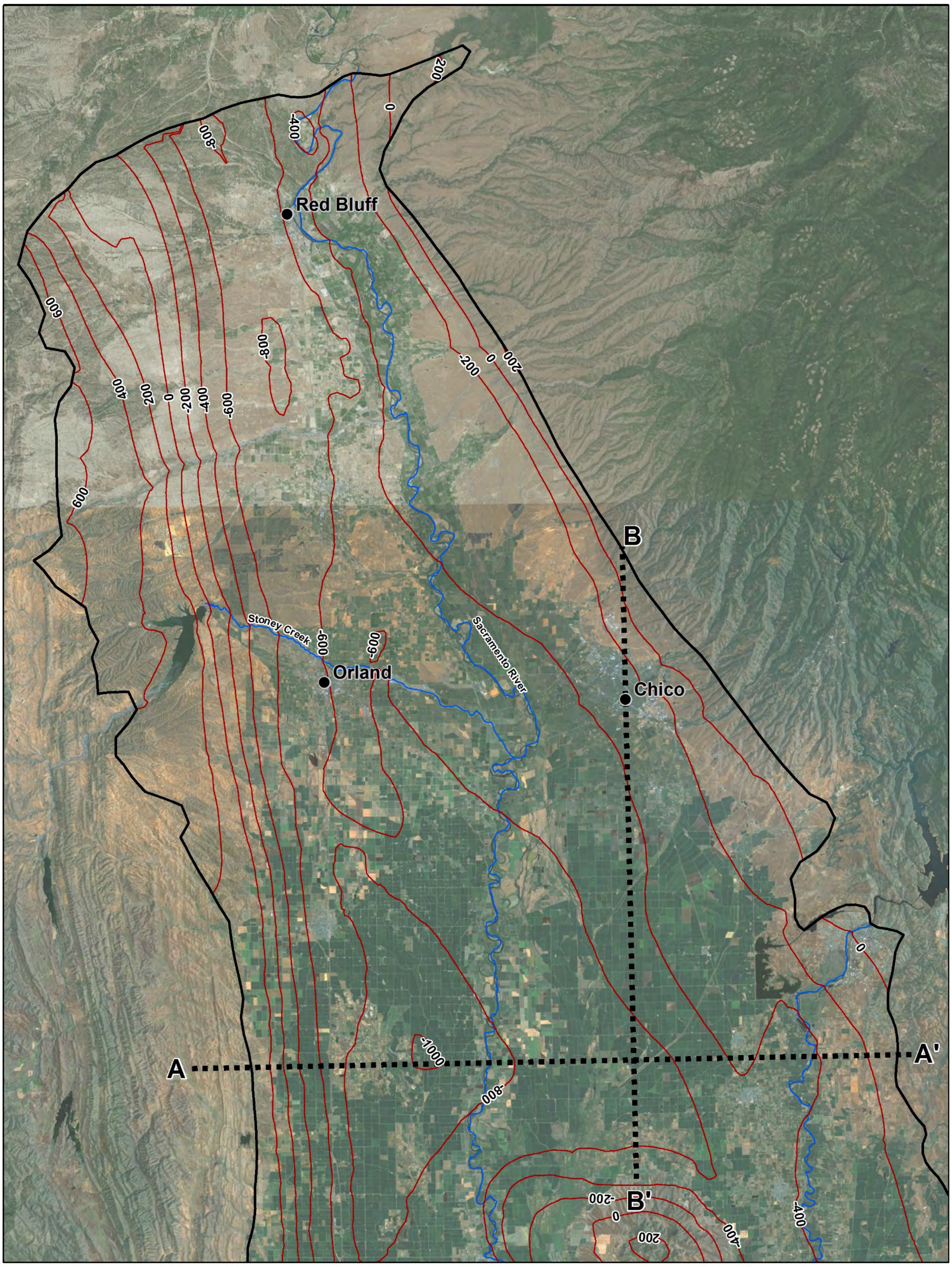

LEGEND

- City
- Major Stream
- SACFEM2013 Model Boundary
- Cross-Section Location
- Contour of Equal Elevation Top of Model Layer 6 (feet NAVD88)

Note:
NAVD88 = North American Vertical Datum of 1988

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

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Figure 9
Elevation of the Top of Model Layer 6
SACFEM2013: Sacramento Valley Finite Element Groundwater Flow Model
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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 Kh. The final step in the process was to smooth the Kh 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 Kh estimate in terms of the available surrounding estimates. When this program is executed, each Kh value is considered in conjunction with all others present within a user-specified critical radius, and the geometric mean of the available Kh 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 approximately 6 miles (10,000 meters). The point values obtained by this process were then gridded to develop a Kh distribution across the model domain. The aquifer transmissivity at each model node within each model layer was then computed using the geometric mean Kh 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 Kh distributions, and it was, therefore, assumed that the computed mean Kh values were representative of the major aquifer units in all model layers.

The distribution of Kh was used as a calibration parameter for SACFEM2013, and minor adjustments were made during the calibration process. Figures 12 and 13 present the final Kh distributions for model Layers 1 through 5 and model Layers 6 and 7. The final distribution of Kh in model Layer 1 is slightly lower than model Layers 2 through 5 east of Dunnigan Hills; however, this is not readily apparent given the 20-foot contour interval on Figure 12. Further, bedrock areas within the interior of the SVGB were assigned Kh values of 1 foot per day in all model layers.

3.2.2.2 Vertical Resistance

MicroFEM computes vertical flow between adjacent model layers based on the simulated head difference between adjacent model layers and the vertical resistance term. The vertical resistance term in MicroFEM is calculated as follows:

$$c = \left(AF \times \frac{mt_i^2 \div 2}{t_i}\right) + \left(AF \times \frac{mt_{i+1}^2 \div 2}{t_{i+1}}\right) \quad (2)$$

Where:

c = Vertical resistance to flow between an upper model layer (i) and adjacent lower model layer (i+1) ($days^{-1}$)

AF = Anisotropy factor (ratio of horizontal to vertical hydraulic conductivity [Kh:Kv])

Kv = Vertical hydraulic conductivity

mt_i = Saturated thickness of model layer i (length [L])

mt_{i+1} = Saturated thickness of model layer i+1 (L)

t_i = Transmissivity of model layer i (L^2/time [T])

t_i+1 = Transmissivity of model layer i (L^2/T)

The Kh:Kv values were assumed to be 500:1 in Layers 2 through 7 and 50:1 in Layer 1 at all model nodes except those representing bedrock areas. The Kh:Kv in areas of bedrock outcrop (such as the Sutter Buttes, Black Butte, and Dunnigan Hills) was assumed to be 1:1 in all model layers.

3.2.2.3 Aquifer Storage

The specific yield of model Layer 1 was assumed to be 12 percent throughout the SACFEM2013 model domain. The aquifer storativity of model Layers 2 through 7 is 6.5×10^{-5} multiplied by model layer thickness throughout the majority of the model domain, with variations along small portions of the model boundary.

3.2.3 Model Time Discretization

Time is continuous in the physical system, but a numerical model must describe the field problem at discrete time intervals. SACFEM2013 was set up to simulate transient flow conditions between WY1970 and WY2010. The period WY1970 through WY2010 was used because it includes very wet periods such as the winter of WY1983, as well as dry periods such as the WY1976 to WY1977 and WY1988 through WY1992 droughts. Using a climatic period of this type allows for assessing model accuracy and the water budgeting process and 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. The 41-year simulation was discretized with monthly stress periods. As such, model stresses (such as stream stage, groundwater pumping, deep percolation) and model output are assigned/evaluated monthly.

3.2.4 Boundary Conditions

Boundary conditions are mathematical statements describing either the head or the groundwater flux within a model domain (Anderson and Woessner, 1992). Correct selection of boundary conditions is a critical step in model construction because boundaries largely determine the flow pattern in steady-state models. Boundary conditions can represent either physical boundaries, such as impermeable rock, or hydraulic boundaries, such as groundwater divides or streamlines. The following types of boundary conditions are used with the SACFEM2013:

- **Head-dependent flux:** The flux across the boundary is calculated as a function of a defined head and a resistance term (which regulates seepage) by using an appropriate governing flow equation.
- **Specified-flux:** A prescribed groundwater flux is defined along the boundary or within the model domain.

3.2.4.1 Head-dependent Flux Boundaries

Groundwater-Surface Water Interaction. A head-dependent boundary condition was chosen to simulate the major streams, flood bypasses, and reservoirs within the SVGB. The MicroFEM wadi system was used to implement streams within the model domain. MicroFEM's wadi package is a two-way, head-dependent boundary condition (that is, it can act as a source of groundwater recharge or as a groundwater sink) that 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:

$$Q_{outflow} = a * (h1 - wh1) / wc1 \quad (3)$$

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

$$Q_{inflow} = a * (wh1 - h1) / wc1 \quad (4)$$

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

$$Q_{inflow} = a * (wh1 - wl1) / wc1 \quad (5)$$

Where:

Q	=	volumetric flux (L^3/T)
a	=	nodal area (L^2)
h1	=	simulated groundwater elevation in layer 1 (L)
wh1	=	simulated stream stage (L)
wl1	=	stream bottom elevation (L)
wc1	=	resistance across the streambed (T^{-1})

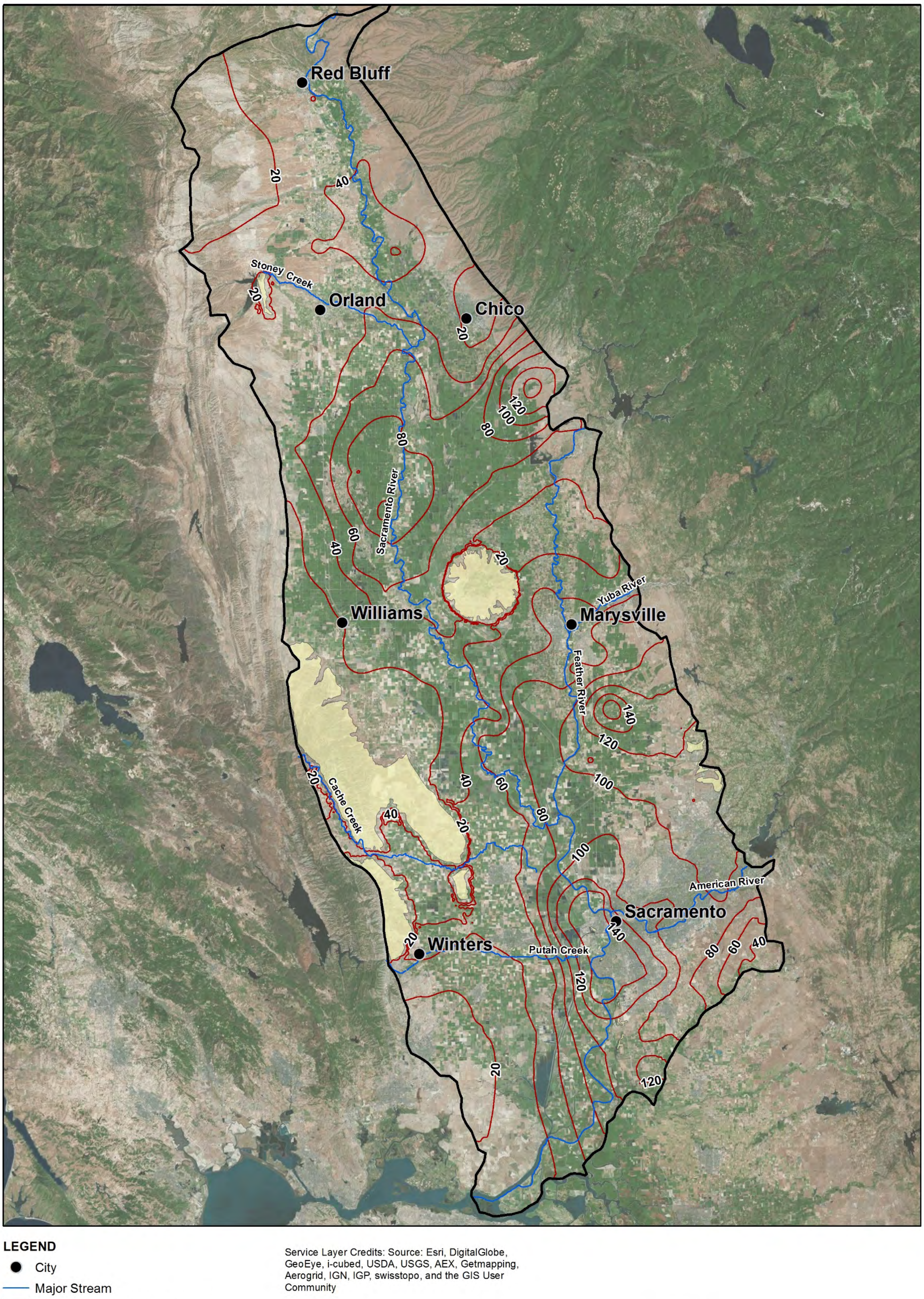

Figure 12
Distribution of Horizontal Hydraulic Conductivity Model Layers 1 through 5
SACFEM2013: Sacramento Valley Finite Element Groundwater Flow Model
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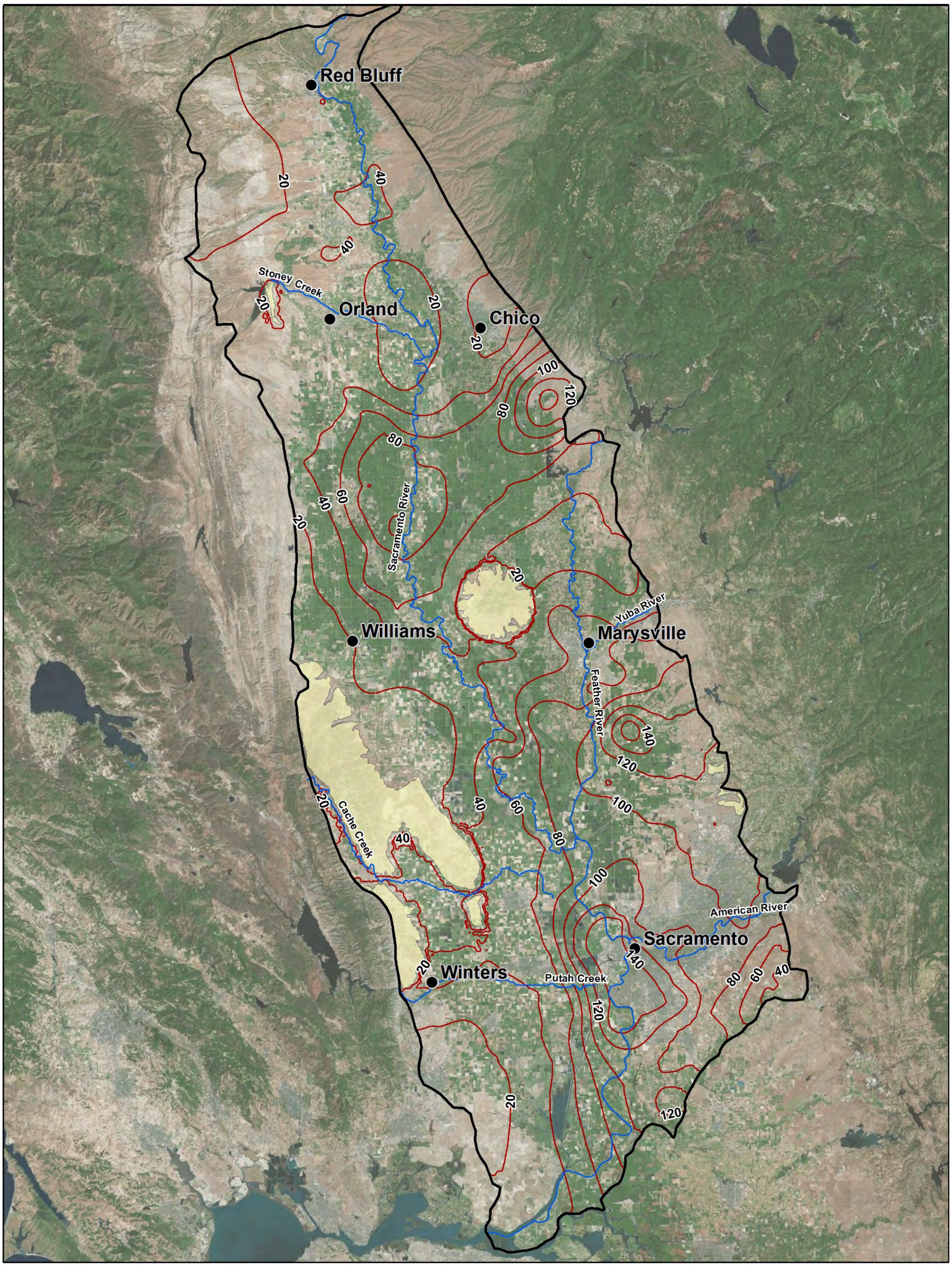

LEGEND

- City
- Major Stream
- SACFEM2013 Model Boundary
- SACFEM2013 Bedrock Outcrop Areas
- Contour of Equal Horizontal Hydraulic Conductivity (feet per day)

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

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Figure 13
Distribution of Horizontal Hydraulic Conductivity Model Layers 6 and 7
SACFEM2013: Sacramento Valley Finite Element Groundwater Flow Model
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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 of 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; the wadi resistance term (wc1) is a measure of the resistivity of the streambed sediments. The resistances are calculated as follows:

$$wc1 = Dr/Kv * (a/LW) \qquad (6)$$

Where:

Dr	=	thickness of streambed sediments (L)
Kv	=	vertical hydraulic conductivity of streambed sediments (L/T)
L	=	stream length represented by the model node (L)
W	=	field width of the wetted river channel within the stream reach represented by L (L)

Fifty individual streams are simulated with MicroFEM's wadi package in the current version of SACFEM2013. Stream locations were digitized from existing base maps and USGS topographic quad sheets and imported into the model domain. Figure 14 presents the locations of surface water features included in SACFEM2013. 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 Kv were based on the type of streambed deposits expected given stream size. Further, the streambed Kv for individual streams was included as a calibration parameter for SACFEM2013. Figure 15 presents the final distribution of streambed Kv. These data are also included in Table 2. Streams draining the Sierra Nevada were generally assigned lower streambed Kv values, with all streams except the Bear River and Big Chico Creek having values of 6.6 ft/day (0.0023 centimeters per second [cm/s]) or less. Westside streams were assigned higher values, with most having assigned Kv values greater than or equal to 16.4 ft/day (0.0058 cm/sec).

Wetted stream width was calculated from aerial photographs at two locations along each stream. Table 3 presents the average wetted stream width included in SACFEM2013. Few streams showed greater variability in width to necessitate developing a continuously variable distribution along the stream length. This was accomplished by estimating wetted stream width at several points via examination of aerial photographs and fitting a polynomial to the data points to interpolate between the measured points. The ranges of wetted stream width are included in Table 3 for these streams.

Representation of Streams. Previous versions of SACFEM included average stream stage elevations (wh1) in the model simulations that did not vary through time. SACFEM2013 incorporates transient stream stage elevations to improve the representation of stream-groundwater interaction under varying hydrologic conditions. Review of historical river stage data shows that stage along the Sacramento and Feather rivers can vary by up to approximately 20 feet between high winter flows and low summer flows. Figure 16 is a plot of historical stage data for the Sacramento and Feather Rivers that illustrates this variability.

A data set of transient stream stage (wh1) was developed for use in SACFEM2013. This involved multiple steps and several assumptions as described in the following sections. There are 55 rivers, streams, and surface water canals or drains and reservoirs explicitly represented in SACFEM2013 (see Figure 14). These 55 surface water features are represented by approximately 5,500 model nodes. As discussed in Section 2.1, SACFEM2013 simulates a 41-year period from WY1970 through WY2010 with 492 monthly time-steps. Therefore, transient stream stage inputs for SACFEM2013 number approximately 2.7 million separate inputs for the entire simulation period (i.e., 5,500 nodes multiplied by 492 time-steps).

Estimating Streambed Elevations. The first step in developing transient stream stage inputs was to estimate the streambed elevation for each stream node. MicroFEM input for stream boundary conditions consists of a water surface elevation (WSE) for each node that must relate to the model streambed elevation for the node. Streambed elevations must also relate to model ground surface elevation for surrounding nodes. Therefore, a consistent vertical datum must be used for ground surface, streambed, and WSE.

The ground surface in SACFEM2013 is based on 30-meter digital elevation model (DEM) data. Model ground surface was developed through a GIS analysis that intersected the SACFEM2013 grid with 30-meter DEM data and calculated statistics for areas that contribute to each SACFEM2013 node. Statistics include the maximum, minimum, and mean elevations for areas that contribute to each node. Ground surface elevation for each node was assumed to be equal to the mean DEM elevation. An initial streambed elevation was estimated as the minimum DEM elevation for the area that contributes to each stream node.

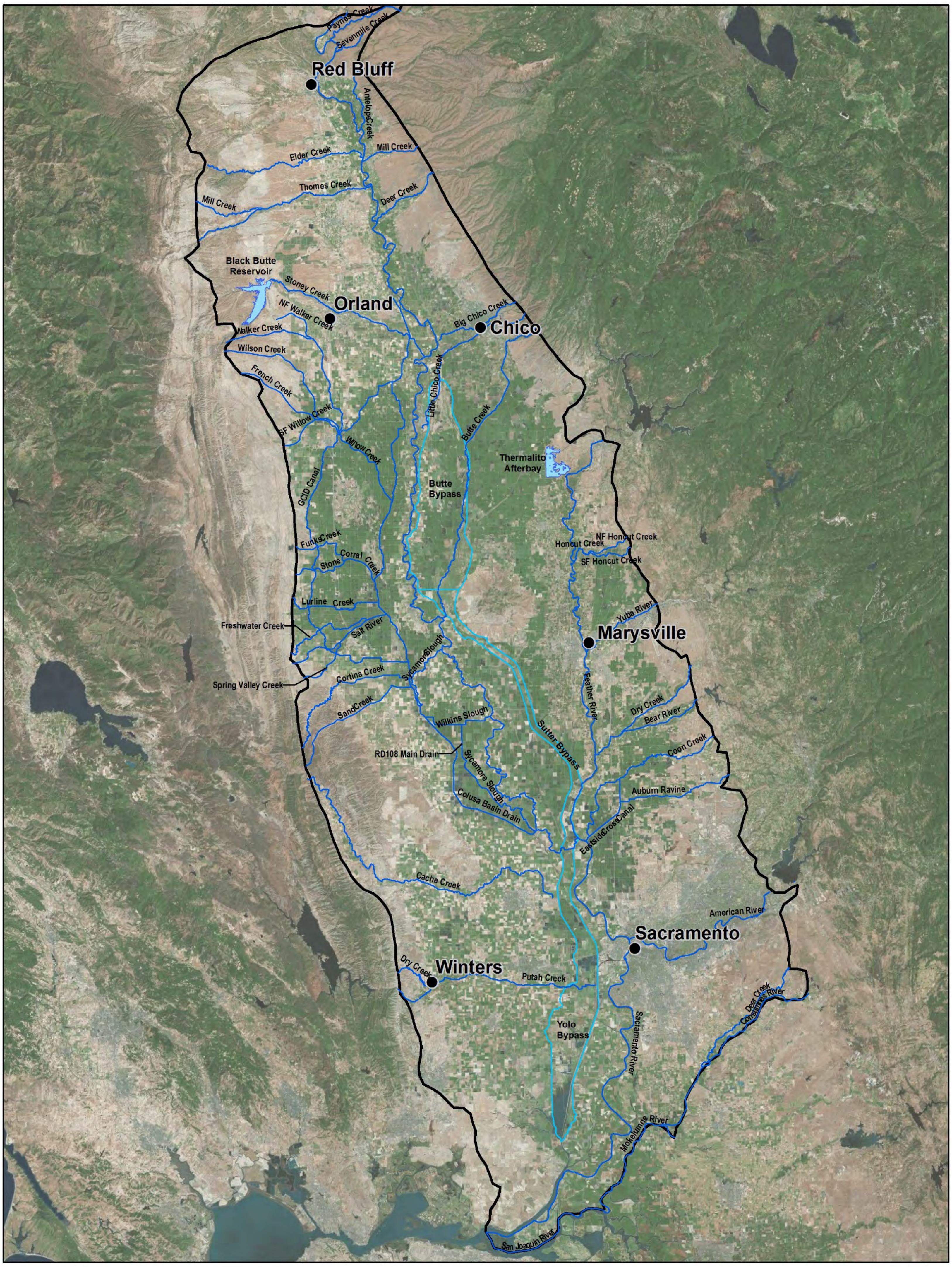
Minimum DEM elevations, or initial streambed elevations, for each stream were reviewed and plotted versus stream node distance from the confluence. These plots illustrate initial streambed elevation based on DEM data from downstream to upstream. Figure 17 is an example of the initial streambed elevation data for all Sacramento River stream nodes.

Review of initial streambed elevations for many streams showed unrealistic increases and decreases in streambed elevations between nodes. For the Sacramento River, minimum DEM elevations provided streambed elevations that are generally flat in the lower reaches of the Sacramento River in and near the Sacramento-San Joaquin River Delta, and a steeper streambed slope at the upstream end of the model. These are expected results based on the topography of the Sacramento Valley. However, there are also areas of significant variation in streambed elevation such as the reach between 75 and 100 miles upstream from the confluence with the San Joaquin River (see Figure 17). These variations illustrate limitations of using 30-meter DEM data and GIS analysis to estimate streambed elevation. Therefore, for each stream, a polynomial trend line was fit through the minimum DEM elevations to provide a more ordered set of streambed elevations. Figure 18 illustrates the trend line used to estimate streambed elevation along the Sacramento River. The trend line provides a set of well-ordered streambed elevations that decrease from upstream to downstream while generally following the topography of the basin.

Stream Stage. A well-ordered estimate of streambed elevation is needed to best utilize available stage and flow data. SACFEM2013 stream stage inputs were developed to represent historical stage that occurred in each surface water feature. Therefore, historical stream stage and flow data were collected and analyzed. These data were collected from a variety of sources including USGS records, DWR gage records and publications, and available data from local water districts and agencies. Available stream stage data are frequently based on different vertical datums, including elevations for individual gages that cannot be related to a standard vertical datum such as North American Vertical Datum of 1988 (NAVD 88). Therefore, it is not possible to establish a consistent vertical datum for all available stage and flow data. Additionally, many gaged streams report only stream flow, not stage, and rating curves are not readily available for most of these streams, or if available, rating curves do not provide the vertical datum.

To utilize as much of the available gage data as possible while addressing the issue of multiple or unknown vertical datums, historical stage data were assumed to approximate stream depth above the streambed elevation. Historical stream depths were then added to estimated streambed elevations to determine water surface elevations for input into SACFEM2013.

There were multiple challenges to develop a complete and realistic dataset of water surface elevations for all surface water features in SACFEM2013. These challenges included estimates for ungaged streams or gaged streams with an incomplete record, estimates for stage along the entire length of the stream based on a single gage location, and methods to estimate water surface elevations at stream confluences.



LEGEND

- ● City
- SACFEM2013 Stream
- Flood Bypass
- SACFEM2013 Model Boundary

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

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Figure 14
SACFEM2013 Surface Water Features
SACFEM2013: Sacramento Valley Finite Element Groundwater Flow Model
USER'S MANUAL

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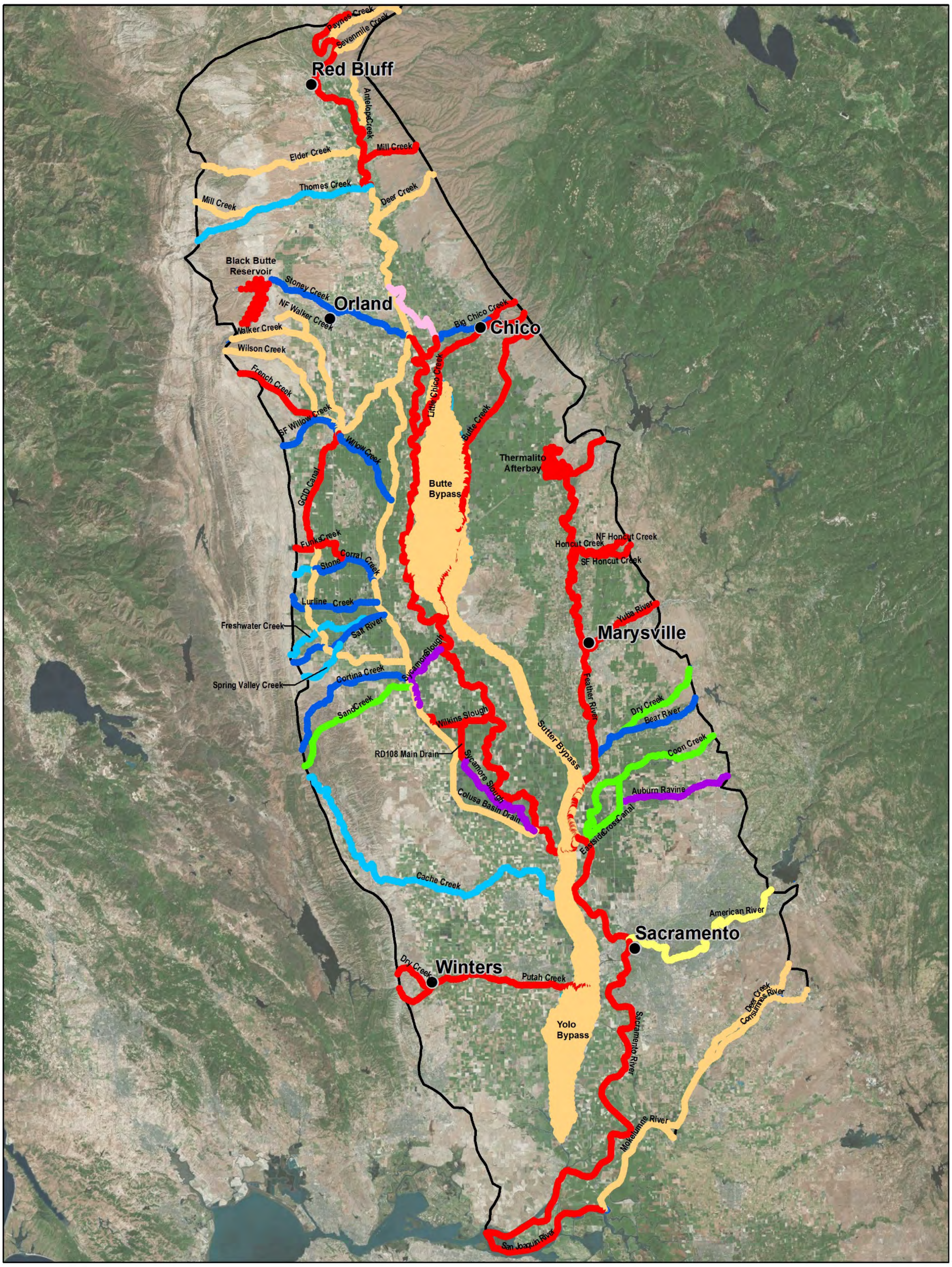

LEGEND

- ● City
- ▭ SACFEM2013 Model Boundary

Streambed Vertical Hydraulic Conductivity (feet per day)

0.1	3.3
0.3	6.6
0.6	16.4
1.6	32.8

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

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Figure 15
Distribution of Vertical Hydraulic Conductivity, Surface Water Features
SACFEM2013: Sacramento Valley Finite Element Groundwater Flow Model
USER'S MANUAL

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TABLE 2
Assumed Streambed Vertical Hydraulic Conductivity
SACFEM2013, Sacramento Valley Finite Element Groundwater Model, User's Manual

Stream	Vertical Hydraulic Conductivity (foot/day)	Vertical Hydraulic Conductivity (centimeters/second)
American River	0.1	3.47E-05
Antelope Creek	0.3	1.16E-04
Auburn Ravine	0.7	2.31E-04
Bear River	32.8	1.16E-02
Big Chico Creek	3.3 – 32.8	1.16E-03 – 1.16E-02
Black Butte Reservoir	3.3	1.16E-03
Butte Bypass	0.3	1.16E-04
Butte Creek	3.3	1.16E-03
Cache Creek	16.4	5.79E-03
Colusa Basin Drain	0.3	1.16E-04
Consumnes River	0.3	1.16E-04
Coon Creek	6.6	2.31E-03
Cortina Creek	32.8	1.16E-02
Deer Creek (Tehama County)	0.3	1.16E-04
Deer Creek (Sacramento County)	0.3	1.16E-04
Dry Creek (Yolo County)	3.3	1.16E-03
Dry Creek (Yuba County)	6.6	2.31E-03
Eastside Cross Canal	6.6	2.31E-03
Elder Creek	0.3	1.16E-04
Feather River	3.3	1.16E-03
French Creek	3.3	1.16E-03
Freshwater Creek	16.4	5.79E-03
Funks Creek	3.3	1.16E-03
Glen Colusa Irrigation District Canal	0.3 – 3.3	1.16E-04 – 1.16E-03
Honcut Creek	3.3	1.16E-03
Little Chico Creek	3.3	1.16E-03
Lurline Creek	32.8	1.16E-02
Mill Creek (Eastern Tehama County)	3.3	1.16E-03
Mill Creek (Western Tehama County)	0.3	1.16E-04
Mokelumne River	0.3	1.16E-04
North Honcut Creek	3.3	1.16E-03
North Fork Walker Creek	0.3	1.16E-04
Paynes Creek	0.3	1.16E-04
Putah Creek	3.3	1.16E-03
RD108 Main Drain	3.3	1.16E-03
South Honcut Creek	3.3	1.16E-03
Sacramento River	0.3 – 3.3	1.16E-04 – 1.16E-03

TABLE 2
Assumed Streambed Vertical Hydraulic Conductivity
SACFEM2013, Sacramento Valley Finite Element Groundwater Model, User's Manual

Stream	Vertical Hydraulic Conductivity (foot/day)	Vertical Hydraulic Conductivity (centimeters/second)
Salt River	32.8	1.16E-02
San Joaquin River	3.3	1.16E-03
Sand Creek	6.6	2.31E-03
Seven Mile Creek	0.3	1.16E-04
South Fork Willow Creek	32.8	1.16E-02
Spring Valley Creek	16.4	5.79E-03
Stone Corral Creek	16.4 – 32.8	5.79E-03 – 1.16E-02
Stoney Creek	3.3 – 32.8	1.16E-03 – 1.16E-02
Sutter Bypass	0.3	1.16E-04
Lower Sycamore Slough	0.7	2.31E-04
Thermalito	3.3	1.16E-03
Thomes Creek	16.4	5.79E-03
Walker Creek	0.3	1.16E-04
Wilkins Slough Canal	3.3	1.16E-03
Willow Creek	32.8	1.16E-02
Wilson Creek	0.3	1.16E-04
Yolo Bypass	0.3	1.16E-04
Yuba River	3.3	1.16E-03

TABLE 3
Wetted Stream Width Values
SACFEM2013, Sacramento Valley Finite Element Groundwater Model, User's Manual

Stream Name	Wetted Stream Width (feet)
American River	394
Antelope Creek	49
Auburn Ravine	33
Bear River	91 – 167
Big Chico Creek	49
Butte Creek	43 – 144
Cache Creek	39 – 108
Colusa Basin Drain	24 – 100
	98
Coon Creek	49
Cortina Creek	33
Deer Creek (Tehama County)	66
Deer Creek (Sacramento County)	49

TABLE 3
Wetted Stream Width Values
SACFEM2013, Sacramento Valley Finite Element Groundwater Model, User's Manual

Stream Name	Wetted Stream Width (feet)
Dry Creek (Yuba County)	49
Dry Creek (Yolo County)	49
Eastside Cross Canal	49
Elder Creek	13 – 79
Feather River	233 – 758
French Creek	16
Freshwater Creek	33
Funks Creek	33
Glen Colusa Irrigation District Canal	43 – 242
Honcut Creek	49
Little Chico Creek	20 – 144
Lurline Creek	33
Mill Creek (Eastern Tehama County)	49
Mill Creek (Western Tehama County)	33
Mokelumne River	312
North Fork Walker Creek	33
North Honcut Creek	66
Paynes Creek	33
Putah Creek	61 – 95
RD108 Main Drain	65
Sacramento River	230 – 4,433
Salt River	16
San Joaquin River	3,248
Sand Creek	33
Sevenmile Creek	33
South Fork Willow Creek	33
South Honcut Creek	49
Spring Valley Creek	16
Stone Corral Creek	33
Stoney Creek	56 – 131
Sycamore Slough	10 – 115
Thomes Creek	49
Walker Creek	49
Wilkins Slough Canal	49
Willow Creek	33
Wilson Creek	33
Yuba River	230 – 356

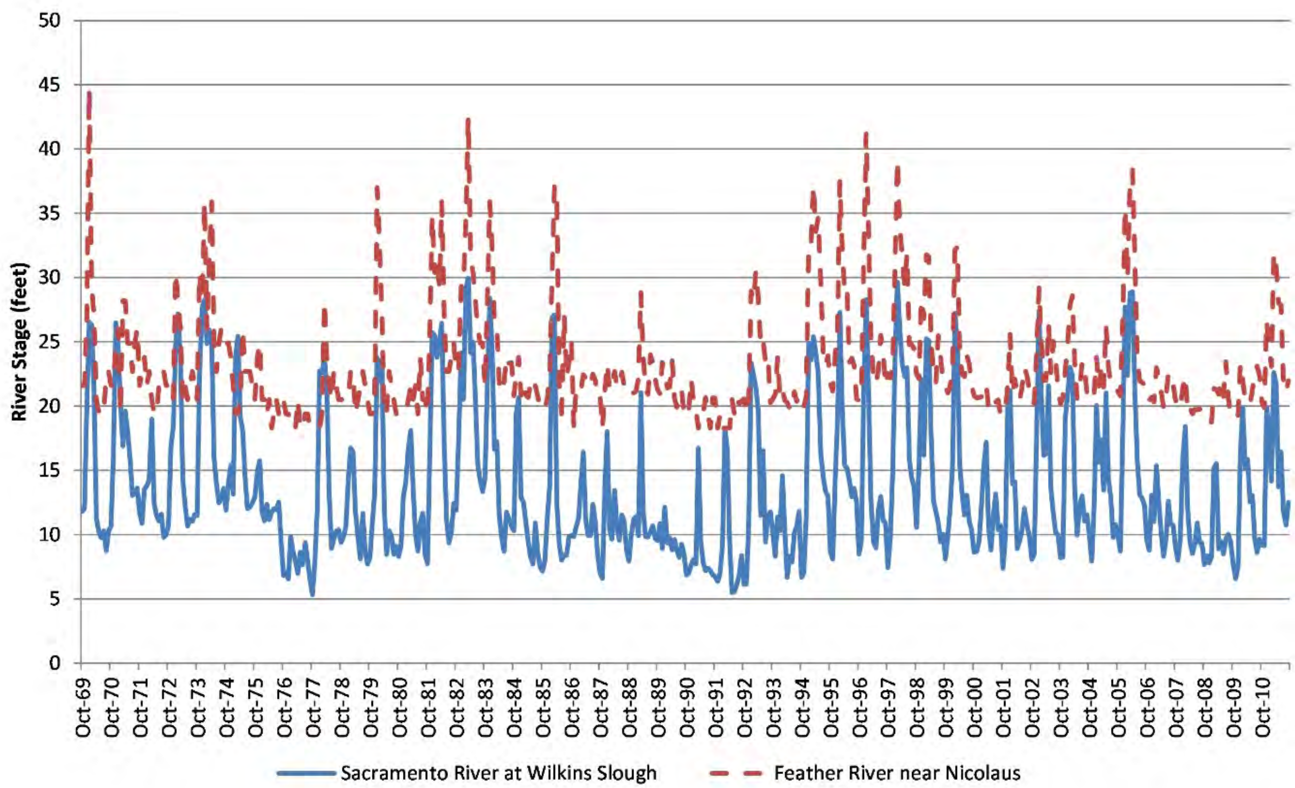

Figure 16
Historical Sacramento and Feather River Stage
SACFEM2013: Sacramento Valley Finite Element Groundwater Flow Model
USER'S MANUAL

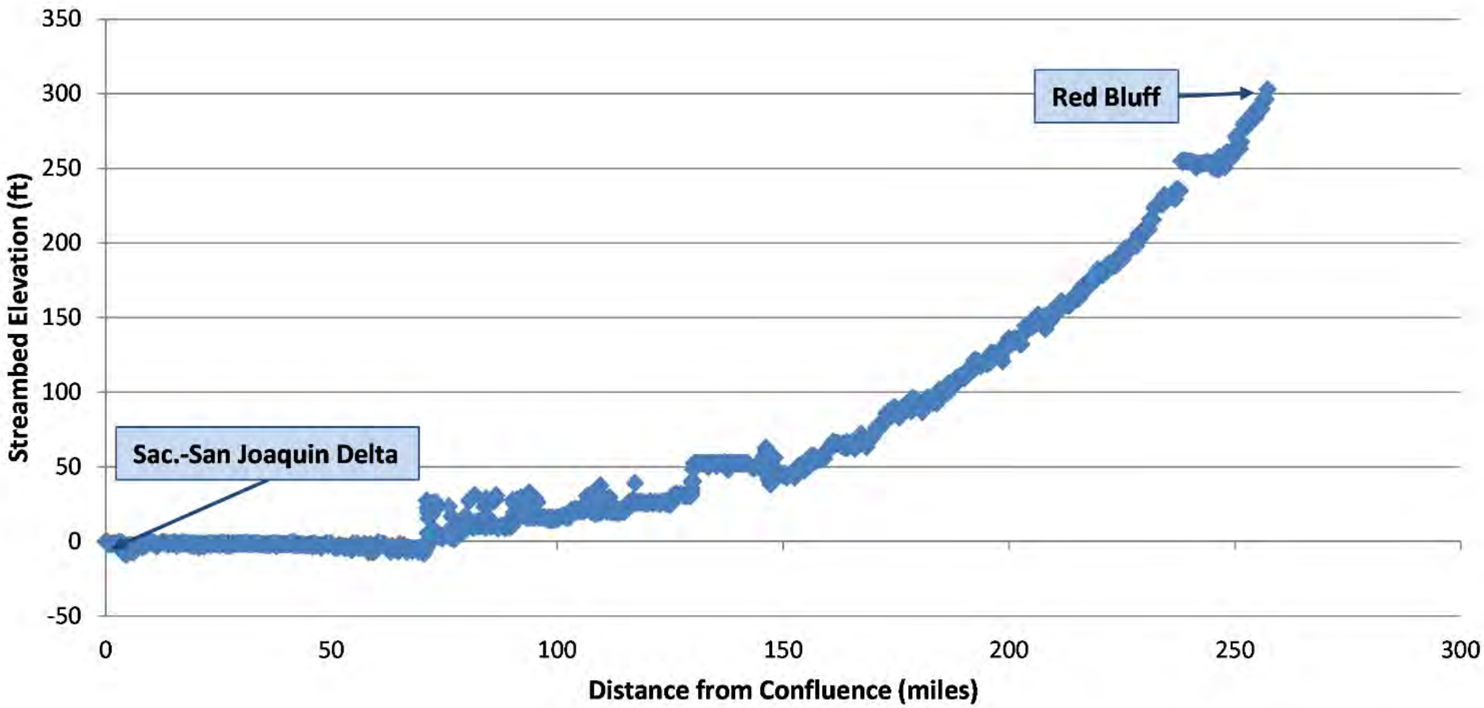

Figure 17
Initial Sacramento River Streambed Elevation based on 30-meter Digital Elevation Model Data
SACFEM2013: Sacramento Valley Finite Element Groundwater Flow Model
USER'S MANUAL

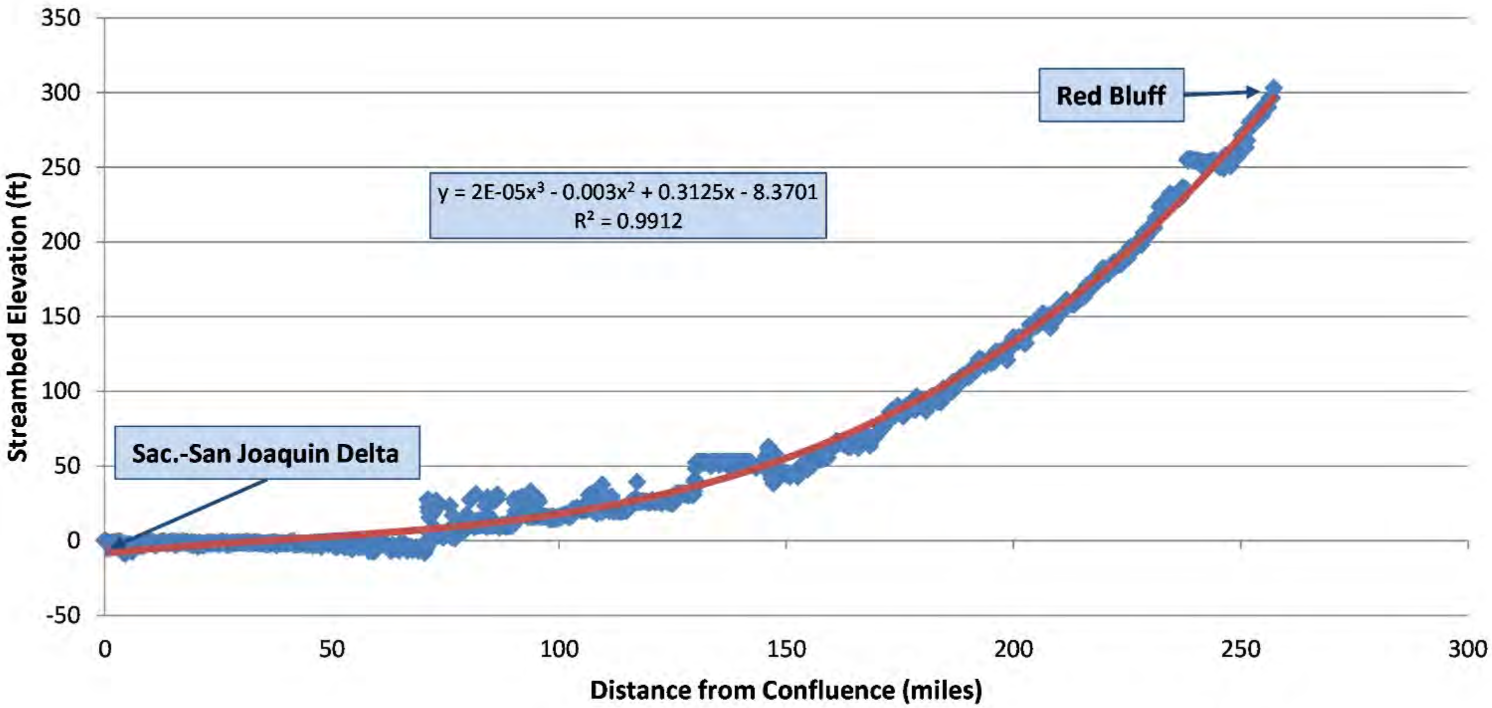

Figure 18
Sacramento River
Streambed Elevation based on Regression Trendline
SACFEM2013: Sacramento Valley Finite Element Groundwater Flow Model
USER'S MANUAL

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Ungaged Streams and Incomplete Records. Review of available stream stage and flow data identified available records for all or a part of the simulation period for 35 streams and canals explicitly represented in SACFEM2013. The remaining surface water features were estimated using data from nearby and similar gaged streams. The majority of ungaged streams are small streams on the west side of the Colusa Basin or small streams near the Bear River. Incomplete gage records were extended or missing periods filled by correlation with nearby and similar streams with complete records, when an adequate correlation could be developed. When an adequate correlation could not be developed, these streams were estimated based on nearby and similar gaged streams.

Stage along Length of Streams. Most gaged streams are gaged at only one location along the entire length of the stream. This information provides one data point on stream stage that must then be extended along the entire length of the stream for all stream nodes. Absent any additional data, it was assumed that depth of water at the gage location is uniform along the length of the stream. Multiple factors can affect stream stage along the length of the stream including watershed area contributing to flow, diversions and return flows from the stream, channel geometry, and others. Attempting to research and account for all such factors for each stream would be a significant undertaking beyond the scope of this project. Exceptions to this assumption are the Sacramento and Feather Rivers. Multiple gages for flow or stage exist along these two rivers, and these gages were used to develop SACFEM2013 inputs. Table 4 shows the gage data used to estimate stream depth along each river.

TABLE 4
Gage Locations Used to Estimate Sacramento and Feather River Stage
SACFEM2013, Sacramento Valley Finite Element Groundwater Model, User's Manual

Sacramento River Gages	Feather River Gages
Bend Bridge	Gridley
Colusa	Yuba City
Wilkins Slough	Nicolaus
Verona	
Freeport	

Water depth at stream nodes nearest gage locations was set equal to the gage record. Water depth at stream nodes between each gage location was interpolated based on stream distance. Water depths at stream nodes upstream of the most upstream gage (i.e., Bend Bridge on the Sacramento River and Gridley on the Feather River) were assumed to equal depth at the gage. Water depths in the Sacramento River downstream of Freeport were assumed to equal water depth at Freeport. Water depths in the Feather River between Nicolaus and the confluence with the Sacramento River were determined based on gage data at Nicolaus and the estimate of Sacramento River water surface elevation at the confluence as described in the following section.

Stream Confluences. An additional review was undertaken and adjustment was made where tributary streams join the Sacramento and Feather Rivers. In some streams and time-steps, WSE in tributary stream nodes at the downstream end of the stream was below the calculated WSE in the trunk stream where the tributary entered. For these tributary streams and time-steps, the WSE in the tributary stream nodes was set equal to the WSE in the trunk stream to represent a back-water effect at the confluence. This adjustment was made at each tributary stream node where the calculated WSE was less than that in the trunk stream for the given time-step.

Review and Quality Assurance. WSE inputs were calculated for each of the approximately 5,500 stream and canal nodes simulated in SACFEM2013 for each of the 492 model time-steps. A spreadsheet was developed to plot streambed and water surface elevation for a given stream and time-step as a method to review and check the input files. A plot for each time-step was created and saved for a given stream, and all plots were compiled into a single audio video interleave (AVI) file to illustrate stream WSE throughout the simulation period. AVI files were reviewed to ensure that input WSEs were reasonable and varied appropriately through time.

Figure 19 is an example of individual time-step plots for the American River WSE. Figure 19 illustrates WSE and the streambed in February 1986 during a large flood event, and August 1992 during a critical drought.

Figure 19 illustrates change in American River WSE for these two months. Figures such as these were developed for each time-step and reviewed to ensure WSE increased and decreased appropriately through time and relative to simulated streambed elevation. These figures also illustrate how WSE at the downstream end of the American River was adjusted based on the WSE in the Sacramento River in these time-steps. WSE at nodes in the downstream end of the American River is controlled by stage in the Sacramento River in both figures. WSE in these nodes was set equal to the WSE in the Sacramento River at the confluence with the American to represent back-water effects in the lower American River and avoid having adjacent stream nodes with significant differences in simulated WSE.

Representation of Flood Bypasses. A similar process was used to estimate water surface elevation within flood bypass areas in the SVGB. These areas differ from stream nodes in that the majority of nodes within the flood bypass areas are typically dry. However, during wet periods some or all of these nodes are flooded and represent a source of aquifer recharge in SACFEM2013.

<u>**Definition of Flood Bypass Areas**</u>. The first step in calculating WSE inputs in flood bypass areas was to delineate areas within the three major flood bypasses of the Butte Basin, Sutter Bypass, and Yolo Bypass. Each of these three major areas was further divided into sub-areas based on locations of major inflows or outflows. Existing GIS data on locations of levees and bypasses were used to identify bypass areas. Figure 20 illustrates the flood levee locations and the polygons used to represent the flood bypass areas and where those areas were subdivided.

After flood bypass areas were identified in GIS, bypass areas were intersected with the SACFEM2013 model grid to identify model nodes within bypass areas. This process identified 15,742 model nodes within bypass areas. Model ground surface elevation for these nodes was also identified based on 30-meter DEM data statistics for the area contributing to each node. The minimum elevation from the GIS intersection with DEM data was used as ground surface for nodes within bypass areas.

The approach to calculate WSE within flood bypass areas differs from that used for streams and other surface water features. An actual WSE was calculated based on historical flow data and flow-stage relationships from existing hydraulic models of the Sacramento River flood control system. Historical flow data were compiled from a variety of sources including USGS gage records and DWR's Water Data Library and California Data Exchange Center. Flows within bypass areas are from streams such as Butte and Cache Creeks plus flows over the Moulton, Colusa, Tisdale, Fremont, and Sacramento weirs. Flow goes over these weirs and into the bypass areas when stage is high in the Sacramento and Feather Rivers.

Flow was estimated at each of the lines that separate the flood bypass sub-areas on Figure 20. These separating lines represent cross section locations in the hydraulic model. For example, flow was estimated at the horizontal line that separates the upper Butte Basin area (BB1 Upper) from the middle Butte Basin area (BB2 Middle). Streams that contribute to flow in the upper Butte Basin area include Big and Little Chico creeks and Butte Creek. These flows were summed to estimate flow at the cross section between the upper and middle Butte Basin areas. Estimates of flow at downstream cross sections were made by adding additional inflows to the estimated flow at the upstream cross section. For example, flow at the cross section that separates the middle and lower Butte Basin (BB3 Lower) area was estimated by adding spills over the Moulton Weir to flows at the upstream cross section.