Appendix C
Construction Emission Calculations

APPENDIX C

Construction Emission Summary – Well 1

EA/IS and FONSI/MND for ACID Groundwater Production Element Project

Emission Source	Emissions (lb/day)						Emissions (tons)					
	ROG	CO	NO_x	SO_x	PM_{10}	$PM_{2.5}$	ROG	CO	NO_x	SO_x	PM_{10}	$PM_{2.5}$
Well Drilling	3.2	14.5	28.1	0.0025	1.45	1.33	0.016	0.073	0.141	0.00001	0.007	0.007
Well Development/ Aboveground Facilities Construction	2.7	9.4	25.5	0.0016	1.12	1.03	0.027	0.094	0.255	0.00002	0.011	0.010
Maximum Emissions	3.2	14.5	28.1	0.0025	1.4	1.3	0.043	0.167	0.396	0.00003	0.018	0.017

NA = Not applicable

NE = Threshold has not been established

Worker Commute Trips				Emissions (lb/day)					
Construction Phase	# of Workers/day	Days of Work	Miles Travelled per Round Trip	ROG	CO	NO_x	SO_x	PM_{10}	$PM_{2.5}$
Well Drilling	7	10	20	0.016	0.60	0.056	0.0009	0.003	0.002
Well Development	4	20	20	0.009	0.34	0.032	0.0005	0.002	0.001
Aboveground Facilities	5	10	20	0.0115	0.431	0.0401	0.0007	0.0020	0.0018

Round trip mileage represents the distance from the construction site to the nearest city, (in this case, Redding, CA).

Well drilling emissions are based on the assumption that well drilling will occur 7 days per week, with two work crews operating 12 hours each per day.

Well development and aboveground facilities construction emissions are based on the assumption that crews will work 7 days per week, 12 hours per day.

It is assumed that the well development and aboveground facilities construction activities will occur simultaneously.

Offsite Vehicle Emissions			Emissions (lb/day)					
Construction Phase	# of Vehicle Trips	Miles Travelled Roundtrip	ROG	CO	NO_x	SO_x	PM_{10}	$PM_{2.5}$
Cement Delivery Trucks	3	20	0.044	0.712	0.069	0.001	0.010	0.009
Fuel Delivery Trucks	1	20	0.015	0.237	0.023	0.000	0.003	0.003

It is assumed that cement truck deliveries will occur on 4 days during the aboveground construction phase of the project, with three deliveries per day.

It is assumed that fuel truck deliveries will occur weekly during all phases of construction (4 days total).

Emission Source	Emissions (lb/day)						Emissions (tons)					
	ROG	**CO**	**NO_x**	**SO_x**	**PM_{10}**	**$PM_{2.5}$**	**ROG**	**CO**	**NO_x**	**SO_x**	**PM_{10}**	**$PM_{2.5}$**
Well Drilling	3.2	15.3	28.2	0.0038	1.46	1.34	0.016	0.077	0.141	0.00002	0.007	0.007
Well Development/ Aboveground Facilities Construction	2.7	9.9	25.5	0.0024	1.12	1.03	0.027	0.099	0.255	0.00002	0.011	0.010
Maximum Emissions	3.2	15.3	28.2	0.0038	1.5	1.3	0.044	0.176	0.396	0.00004	0.018	0.017

NA = Not applicable
NE = Threshold has not been established

Worker Commute Trips				**Emissions (lb/day)**					
Construction Phase	**# of Workers/day**	**Days of Work**	**Miles Travelled per Round Trip**	**ROG**	**CO**	**NO_x**	**SO_x**	**PM_{10}**	**$PM_{2.5}$**
Well Drilling	7	10	30	0.024	0.91	0.084	0.0014	0.004	0.004
Well Development	4	20	30	0.014	0.52	0.048	0.0008	0.002	0.002
Aboveground Facilities	5	10	30	0.0172	0.647	0.0602	0.0010	0.0030	0.0026

Round trip mileage represents the distance from the construction site to the nearest city (in this case, Redding, CA).
Well drilling emissions are based on the assumption that well drilling will occur 7 days per week, with two work crews operating 12 hours each per day.
Well Development and aboveground facilities construction emissions are based on the assumption that crews will work 7 days per week, 12 hours per day.
It is assumed that the well development and aboveground facilities construction activities will occur simultaneously.

Offsite Vehicle Emissions			**Emissions (lb/day)**					
Construction Phase	**# of Vehicle Trips**	**Miles Travelled Roundtrip**	**ROG**	**CO**	**NO_x**	**SO_x**	**PM_{10}**	**$PM_{2.5}$**
Cement Delivery Trucks	3	30	0.066	1.067	0.104	0.002	0.014	0.013
Fuel Delivery Trucks	1	30	0.022	0.356	0.035	0.001	0.005	0.004

It is assumed that cement truck deliveries will occur on 4 days during the aboveground construction phase of the project, with three deliveries per day.
It is assumed that fuel truck deliveries will occur weekly during all phases of construction (4 days total).

APPENDIX C

Road Emission Factors – Exhaust Emission Factors

EA/IS and FONSI/MND for ACID Groundwater Production Element Project

Vehicle	Vehicle Type in EMFAC2007	2011 Emission Factors (lb/mile)						
		ROG	CO	NOx	SO_x	PM_{10}	$PM_{2.5}$	CO_2
Work Trucks (unpaved roads)	Light-duty truck, gasoline	0.0007	0.0119	0.0012	0.00002	0.0002	0.0001	1.9507
Employee Commute Paved Road	Passenger vehicles, gasoline	0.0001	0.0043	0.0004	0.00001	0.0000	0.00002	0.6320
Vehicle	**Vehicle Type in EMFAC2007**	**2011 Emission Factors (g/mile)**						
		ROG	CO	NO_x	SO_x	PM_{10}	$PM_{2.5}$	CO_2
Work Trucks (unpaved roads)	Light-duty truck, gasoline	0.334	5.38	0.523	0.009	0.1	0.07	884.86
Employee Commute	Passenger vehicles, gasoline	0.052	1.956	0.182	0.003	0.009	0.008	286.666

Emission factors are from the California Air Resources Board's EMFAC 2007 model for Shasta County.

It was assumed that vehicles would travel at 10 miles per hour on unpaved roads and 45 miles per hour on paved roads.

4/29/2011 03:06:46 PM

Urbemis 2007 Version 9.2.4

Detail Report for Summer Construction Unmitigated Emissions (Pounds/Day)

File Name: C:\Projects\Waldrop\ACID urbemis.urb924

Project Name: ACID

Project Location: California State-wide

On-road Vehicle Emissions Based on: Version : Emfac2007 V2.3 Nov 1 2006

Off-road Vehicle Emissions Based on: OFFROAD2007

CONSTRUCTION EMISSION ESTIMATES (Summer Pounds Per Day, Unmitigated)

	ROG	NOx	CO	SO2	PM10 Dust	PM10 Exhaust	PM10 Total	PM2.5 Dust	PM2.5 Exhaust	PM2.5 Total	CO2
Trenching 06/01/2011-06/10/2011	3.15	28.01	13.50	0.00	0.00	1.43	1.44	0.00	1.32	1.32	4,971.40
Trenching Off-road Diesel	3.14	27.99	12.99	0.00	0.00	1.43	1.43	0.00	1.32	1.32	4,920.30
Trenching Worker Trips	0.02	0.03	0.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	51.10
Mass Grading 06/11/2011-06/30/2011	2.72	25.44	9.18	0.00	0.00	1.11	1.12	0.00	1.02	1.02	2,567.06
Mass Grading Dust	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mass Grading Off-road Diesel	2.69	25.40	8.41	0.00	0.00	1.11	1.11	0.00	1.02	1.02	2,490.42
Mass Grading On-road Diesel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mass Grading Worker Trips	0.02	0.04	0.76	0.00	0.00	0.00	0.01	0.00	0.00	0.00	76.64

Phase Assumptions

Phase: Mass Grading 6/11/2011 - 6/30/2011 - Well Development

Total Acres Disturbed: 0

Maximum Daily Acreage Disturbed: 0

Fugitive Dust Level of Detail: Default

0 lbs per acre-day

On-road Truck Travel (VMT): 0

Off-road Equipment:

2 Other Material Handling Equipment (191 hp) operating at a 0.59 load factor for 12 hours per day

1 Tractors/Loaders/Backhoes (108 hp) operating at a 0.55 load factor for 12 hours per day

Phase: Trenching 6/1/2011 - 6/10/2011 - Well Drilling

Off-road Equipment:

1 Bore/Drill Rigs (291 hp) operating at a 0.75 load factor for 20 hours per day

1 Tractors/Loaders/Backhoes (108 hp) operating at a 0.55 load factor for 20 hours per day

Appendix D
Redding Groundwater Basin Finite-Element Model Documentation

Appendix D

Documentation of the Redding Groundwater Basin Finite-Element Model

July 2011

CH2MHILL
2525 Airpark Drive
Redding, California 96001

Contents

Contents, Continued

Acronyms and Abbreviations

ACID	Anderson-Cottonwood Irrigation District
CY	calendar years
DWR	California Department of Water Resources
ET	evapotranspiration
ft	foot or feet
ft^2	square foot or feet
ft^3	cubic foot or feet
GIS	geographic information system
gpd	gallons per day
gpm	gallons per minute
in.	inch or inches
K_h	horizontal hydraulic conductivity
K_v	vertical hydraulic conductivity
PRISM	Parameter-elevation Regressions on Independent Slopes Model
REDFEM	Redding Groundwater Basin Finite-Element Model
RMSE	root mean squared error
SACFEM	Sacramento Valley Finite-Element Groundwater Model
USGS	U.S. Geological Survey

APPENDIX D

Documentation of the Redding Groundwater Basin Finite-Element Model

1.0 Introduction

This report provides an overview of the development and calibration of the Redding Groundwater Basin Finite-Element Model (REDFEM). Rather than providing an exhaustive discussion of the parameter values that comprise REDFEM, the electronic modeling files serve as companion files to this report and are available upon request.

2.0 Modeling Objectives

The current objective for REDFEM is to develop a quantitative tool that forecasts effects of a groundwater production project on surface water and groundwater resources within the Redding Groundwater Basin. Following are additional potential uses of REDFEM:

- Help identify potential consequences of proposed actions before groundwater projects are implemented.
- Assess alternative approaches to proposed actions that could mitigate potential adverse effects on water resources.
- Assess combined effects from multiple proposed or existing projects.
- Help guide resource planning activities to address issues such as water supply reliability, water use efficiency, urbanization, and the environment.
- Enhance current and future water-level monitoring activities.
- Aid in public outreach efforts.

3.0 Model Code Description

MicroFEM (Hemker, 2011), a finite-element based, three-dimensional, integrated groundwater modeling package developed in The Netherlands, was chosen to simulate the groundwater flow system in the Redding Groundwater Basin. 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 code for the following reasons:

- The finite-element scheme allows the construction of a model grid covering a large geographic area (over 822 square miles in the REDFEM domain) with coarse node spacings near the periphery of the basin and finer node spacings in the interior of the basin (such as near potential project areas). The finer node spacing 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 rapid evaluation of transient water budgets for model simulations and identification of changes to stream discharges and other groundwater fluxes across the model domain.
- REDFEM was constructed using codes and a methodology similar to those of the Sacramento Valley Finite-Element Groundwater Model (SACFEM) (CH2M HILL, 2009). The use of similar approaches provides consistency with methods used to forecast potential impacts on groundwater and surface water resources in other areas of the Sacramento Valley (including the Redding Groundwater Basin).
- MicroFEM is the product of more than 20 years of development and has been used in groundwater evaluations worldwide.
- MicroFEM has been benchmarked and verified, meaning numerical solutions generated by the code have been compared with one or more analytical solutions, subject to scientific review, and used on previous modeling projects. Verifying the code ensures that MicroFEM can accurately solve the governing equations that constitute the mathematical model.
- CH2M HILL has experience applying MicroFEM to assess complicated groundwater flow problems at numerous sites.

4.0 Geologic Setting

The Redding Groundwater Basin is located in the northernmost portion of the Sacramento Valley. Underlying Tehama and Shasta Counties, it is bordered by the Klamath Mountains to the north, the Coast Range to the west, and the Cascade Mountains to the east. The Red Bluff Arch, between Cottonwood and Red Bluff, separates the Redding Groundwater Basin from the Sacramento Valley Groundwater Basin to the south.

The Redding Groundwater Basin consists of a sediment-filled, southward-plunging symmetrical trough (California Department of Water Resources [DWR], 2003). Simultaneous deposition of material from the Coast Range and the Cascade Range resulted in two different formations, which are the principal freshwater-bearing formations in the basin. The Tuscan Formation in the east is derived from Cascade Range volcanic sediments, and the Tehama Formation in the western and northwest portion of the basin is derived from Coast Range sediments. These formations are up to 2,000 feet thick near the confluence of the Sacramento River and Cottonwood Creek, and the Tuscan Formation is generally more permeable and productive than the Tehama Formation (Pierce, 1983). The Redding Groundwater Basin covers approximately 510 square miles in parts of Shasta and Tehama Counties, and is the northernmost portion of California's Central Valley (Figure D-1; figures are located at the end of this report). The basin is bounded by the foothills of the Cascade Range to the east, by the Klamath Mountains to the north and northwest, by the northern

Coast Ranges to the southwest, and by the Red Bluff Arch to the south. The Red Bluff Arch is a subsurface uplift located north of the city of Red Bluff, and structurally separates the Redding Groundwater Basin from the Sacramento Valley Groundwater Basin (Pierce, 1983).

The base of freshwater in the basin coincides with the top of the Chico Formation, which is composed of marine deposits of sandstone, conglomerates, and shale, and contains salt water under artesian pressure. Fresh groundwater is found above the Chico Formation in the Tuscan Formation (in the eastern portion of the basin) and in the Tehama Formation in the western portion of the basin. The Tuscan and Tehama Formations are at most 2,000 feet thick near the confluence of the Sacramento River and Cottonwood Creek (Pierce, 1983).

The thick sand and gravel strata (derived from reworked mudflows) of the Tuscan Formation are generally more permeable and productive than the Tehama Formation's fluvial silt, sand, gravel, and clays. The Tuscan and Tehama Formations are generally overlain by the moderately permeable Red Bluff Formation, which is composed of coarse gravels and boulders in a sand, silt, and clay matrix. Unconsolidated moderately permeable alluvial deposits underlie the floodplains of the Sacramento River and its tributaries, and permeability is higher where gravels dominate (Pierce, 1983).

5.0 Hydrology

The Sacramento River is the main surface water feature in the Redding Groundwater Basin, with several tributaries draining the surrounding hills and mountains. The most significant tributaries are Battle, Churn, Clear, Cottonwood, Cow, Little Cow, Stillwater, and Dry Creeks. Groundwater and surface water interaction, and riparian vegetation occur along surface water features throughout the basin.

Seasonal groundwater fluctuations range from 2 to 3 feet in shallow, unconfined aquifers and 2 to 5 feet in semi-confined to confined aquifers in normal years. During drought years, unconfined aquifer levels can fluctuate by as much as 10 feet, and semi-confined and confined aquifer levels can fluctuate as much as 16 feet. In general, groundwater flows southeasterly on the west side of the basin and southwesterly on the east side, toward the Sacramento River.

6.0 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.

6.1 Areal Characteristics of Model Grid

The model boundary follows the Redding Groundwater Basin boundary (Pierce, 1983), except in the north and northwest locations, where the boundary was extended to encompass areas representing water purveyor service areas. This facilitates modeling evaluations of impacts on in-basin water transfers. The REDFEM grid consists of 55,938 nodes and 111,461 elements per layer (see Figure D-2). The current grid configuration supports evaluating potential conjunctive water management projects within the Redding

Groundwater Basin; however, REDFEM was designed to be grid-independent, and geographic information system (GIS)-based tools can be used to build a similar basinwide model on any grid needed to support a particular application. The current grid's nodal spacing varies from a nominal spacing of 1,500 feet near the model boundary, where groundwater projects are not currently being evaluated, to a nominal spacing of 500 feet in the central part of the basin, where groundwater production is being evaluated. The finer node spacing in the interior allows for more refined estimates of the effects of groundwater pumping on groundwater levels and groundwater and surface water interaction in the proposed project area.

6.2 Vertical Characteristics of Model Grid

REDFEM is vertically stacked into four layers to provide a three-dimensional representation of the subsurface system. These layers were developed to provide sufficient vertical resolution to facilitate the following:

- Evaluation of the effects of groundwater pumping on shallow and regional water resources
- Assignment of pumping stresses to appropriate depths within the aquifer that reflect the major producing zones within the aquifer system

The total model thickness represents the thickness of the freshwater aquifer above the Chico Formation, as modified from DWR's Bulletin 74-8, *Water Well Standards Shasta County* (DWR, 1968) (Figure D-3). The total modeled thickness was established by subtracting the depth to the Chico Formation from the average groundwater levels. Model Layer 1 was assigned a thickness of 50 feet; this layer thickness 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 and riparian areas. Model Layers 2 and 3 represent the more regional groundwater-producing zones within the basin, where municipal and agricultural wells tend to be screened. These layers were assigned thicknesses of 100 and 200 feet, respectively, to provide multiple-depth zones to assign regional pumping. Model Layer 4 represents the remaining saturated thickness above the Chico Formation, which varies from 50 feet at the basin margins to approximately 1,800 feet near the confluence of the Sacramento River and Cottonwood Creek.

6.3 Aquifer Properties

The Redding Groundwater Basin distribution of aquifer properties is poorly understood. In 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, provided valuable information on aquifer properties. However, in the majority of the basin, such data are not available.

Several steps were taken to aid in assigning aquifer properties across the modeling domain representing the Redding Groundwater Basin. Various reports prepared by the Department, the U.S. Geological Survey (USGS), and area consultants were reviewed and, where available, aquifer property data were compiled. Hundreds of well completion logs were obtained from the Northern District of DWR and reviewed for well-construction and specific-capacity information. Aquifer properties were estimated for discrete-depth intervals in the Redding Groundwater Basin (based on the well construction information) and plotted on a basin map. Approximately 90 wells provided both well-construction and specific-capacity information that was used in this analysis. After the data set was finalized, the reported specific capacity data for each well were used to estimate aquifer transmissivity for each location. The following equation is a simplified version of the Jacob nonequilibrium equation (Driscoll, 1986) used to estimate aquifer trasmissivity (Equation -1):

$$SC = \frac{T}{2000} \quad (1)$$

where:

SC = specific capacity of an operating production well (gallons per minute per foot of drawdown [gpm/ft])

T = aquifer transmissivity (gallons per day per foot [gpd/ft])

After a transmissivity estimate was computed for each location with both specific-capacity and well-construction information, the transmissivity value was then divided by the screen length of the production well to yield an estimate of the horizontal hydraulic conductivity (K_h) of the aquifer materials. The point values obtained by this process were then kriged to develop a K_h distribution across the model domain. The aquifer transmissivity at each model node within each model layer was then computed using the hydraulic conductivity value at that node multiplied by 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 initially assumed that the computed mean hydraulic conductivity values were representative of the major aquifer units in all model layers. The ratio of the K_h to vertical hydraulic conductivity (K_v) ranges from 10 to 1, up to 100 to 1 in REDFEM. Figure D-4 shows the distribution of transmissivity used in REDFEM.

The specific yield of the upper 50 feet below the water table (Model Layer 1) was assigned a uniform value of 10 percent. This value was within the range previously reported by Olmsted and Davis (1961) and Pierce (1983). A uniform specific storage coefficient of $2x10^{-6}$ per ft (ft^{-1}) of aquifer thickness was assumed for the remaining levels. The storage coefficient for Model Layers 2 through 4 was computed by multiplying the model layer thickness by $2x10^{-6}$ ft^{-1}.

6.4 Boundary Conditions

Boundary conditions are mathematical statements describing either the groundwater elevation (such as head) or the groundwater flux at specific locations within the model domain (Anderson and Woessner, 1992). Boundary conditions can represent either physical boundaries, such as impermeable rock, or hydraulic boundaries, such as groundwater divides or streamlines. The three types of boundary conditions used in REDFEM are as follows:

- Head-dependent flux boundaries, where the groundwater flux across the boundary is calculated as a function of a calculated head and a conductance term (which regulates seepage)
- Specified-flux boundaries, where a constant groundwater flux is prescribed
- No-flow boundaries, where the groundwater flux across the boundary is prohibited

The following subsections describe the assignment of each of these boundary conditions in REDFEM.

6.4.1 Head-dependent Flux Boundaries

Streams. The MicroFEM wadi system was used to simulate the two-way exchange of water between the modeled streams and underlying aquifer in the study area. MicroFEM's wadi system calculates the magnitude and direction of nodal fluxes on the basis of relative values of stream stage and the modeled water table. For each model node, groundwater discharge to, or recharge from, a stream is calculated according to the following equations (Equations 2 through 4):

$$Q_{outflow} = a\frac{(h1 - wh1)}{wc1}, \text{ if } wh1 < 1 \tag{2}$$

$$Q_{inflow} = a\frac{(wh1 - h1)}{wc1}, \text{ if } wl1 < h1 < wh1 \tag{3}$$

$$Q_{inflow} = a\frac{(wh1 - wl1)}{wc1}, \text{ if } h1 < wl1 \tag{4}$$

where:

$Q_{outflow}$ = modeled groundwater flux from the aquifer to the stream (cubic feet per day [ft^3/day])

Q_{inflow} = modeled groundwater flux from the stream to the aquifer (ft^3/day)

a = nodal area (square-feet [ft^2])

h1 = modeled groundwater elevation (such as head) in Model Layer 1 (ft)

wh1 = modeled stream stage (ft)

wl1 = modeled stream bottom elevation (ft)

wc1 = resistance across the streambed (per day [day^{-1}])

Typically, the area surrounding a model node that represents a discrete reach of a stream is different than the actual surface area of that stream reach in the field. The wc1 term incorporates an areal correction factor to account for this discrepancy. An additional correction factor was incorporated into the wc1 term, to account for the additional flow resistance through sediments in the upper half of Model Layer 1, when calculating Q_{inflow} and $Q_{outflow}$. Thus, the wc1 term is calculated as follows (Equation 5):

$$wc1 = \left(\frac{b_s}{K_{vs}} + \frac{½ b_a}{K_{va}}\right)\left(\frac{a}{LW}\right) \tag{5}$$

where:

b_s = thickness of streambed sediments (ft)
K_{vs} = vertical hydraulic conductivity of streambed sediments (feet per day [ft/day])
b_a = thickness of aquifer represented by Model Layer 1 (ft)
K_{va} = vertical hydraulic conductivity of aquifer represented by Model Layer 1 (ft/day)
L = stream length represented by the model node (ft)
W = field-width of the wetted stream channel along L (ft)

Streams simulated in the model with the wadi system were those with perennial or nearly perennial streamflow, including the Sacramento River, Cow Creek, and Cottonwood Creek (Figure D-5). Stream locations were digitized from existing base maps and topographic quad sheets, and imported into the model domain. Streambed thickness was assumed to be 1 foot for all stream nodes. Streambed K_v assumptions were based on the type of streambed deposits expected, based on relative stream size. Wetted stream width was visually estimated by reviewing aerial photographs.

Drains. The MicroFEM drain system was specified at nodes across the top surface of Model Layer 1, excluding wadi nodes and nodes coinciding with the Anderson-Cottonwood Irrigation District (ACID) main canal. A drain boundary condition is a one-way head-dependent flux boundary allowing groundwater to discharge from the modeled aquifer to the drain, if the modeled water table elevation is greater than the prescribed drain elevation. The drain elevations were set at the land surface elevation to allow the model to simulate groundwater discharge to the land surface. Areas of groundwater discharge to the surface include 29 stream channels in the model domain that are implemented as drains (Figure D-5). Equations 6 and 7 simulate transfer of groundwater from the aquifer to a drain, as follows:

$$Q_{outflow}=a\frac{(h1\text{-}dh1)}{dc1}, \text{if } h1 > dh1 \tag{6}$$

$$Q_{outflow}=0, \text{if } h1 \leq dh1 \tag{7}$$

The parameter dc1 represents the drain resistance and is a measure of the resistance to flow across the drain boundary. Equation 8 computes the dc1 parameter as follows:

$$dc1=\frac{b_d}{K_d} \tag{8}$$

where:

$Q_{outflow}$	=	modeled groundwater flux from the aquifer to the drain (ft^3/day)
a	=	nodal area (ft^2)
h1	=	modeled groundwater elevation (such as head) in Model Layer 1 (ft)
dh1	=	modeled drain elevation (ft)
dc1	=	modeled resistance across the drain (day^{-1})
b_d	=	thickness of drain interface (ft)
K_d	=	hydraulic conductivity of drain interface (ft/day)

Evapotranspiration of Shallow Groundwater. The MicroFEM evapotranspiration (ET) system was specified at all nodes across the top surface of Model Layer 1. This particular boundary condition is a one-way head-dependent flux boundary that allows groundwater to discharge from the modeled aquifer, if the modeled water table elevation is located within a prescribed rooting depth below the land surface. The upper and lower ET elevations were set at the land surface elevation and 5 feet below the land surface elevation, respectively. Equations 9 through 11 simulate the groundwater loss to ET, as follows:

$$Q_{outflow}=a\cdot em1, \text{if } h1 > eh1 \tag{9}$$

$$Q_{outflow}=a\cdot em1\left(\frac{h1-el1}{eh1-el1}\right), \text{if } el1 < 1 < e1 \tag{10}$$

$$Q_{outflow}=0,\ \text{if } h1 \leq el1 \tag{11}$$

where:

$Q_{outflow}$ = modeled groundwater loss to ET (ft^3/day)
a = nodal area (ft^2)
h1 = modeled groundwater elevation (i.e., head) in Model Layer 1 (ft)
eh1 = modeled upper groundwater ET elevation (ft)
el1 = modeled lower groundwater ET elevation (ft)
em1 = modeled maximum ET rate (ft/day)

6.4.2 Specified-flux Boundaries

Three types of specified-flux boundary conditions used within REDFEM include (1) areal groundwater recharge from precipitation and applied water (where applicable), (2) groundwater recharge (such as seepage) from the ACID canal, and (3) groundwater pumping. A detailed discussion of these follows.

Areal Groundwater Recharge from Precipitation and Applied Water. Precipitation grids generated by the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (PRISM Climate Group, 2010) were initially intersected with model nodes representing urban and native vegetation areas using GIS software to estimate rates of groundwater recharge from precipitation falling within areas mapped as urban and native vegetation in the model domain. The PRISM grids contained monthly precipitation rates on 0.5-mile (800-meter) centers. The annual groundwater recharge from precipitation in urban and native vegetation areas was then calculated with the aid of a HYDRUS-1D (Simunek et al., 2008 and 2009) model. Equation 12 shows the mathematical relationship developed from the HYDRUS-1D simulations, as follows:

$$DP_{PPT}=(0.001843)(PPT^{2.5076}) \tag{12}$$

where:

DP_{PPT} = average annual groundwater recharge from precipitation (inches [in.])
PPT = annual precipitation (in.)

The DP_{PPT} was temporally distributed according to the monthly volume of rainfall for the year at a given REDFEM node, up to a maximum of approximately 26 inches per year.

The basis for the spatial distribution and magnitudes of groundwater recharge from applied water are described in full detail in the Agricultural Surface Water Budget and Urban Water Budget sections below.

Groundwater Pumping. Monthly groundwater pumping rates, attributed to municipal, industrial, agricultural, and domestic pumping, were specified at appropriate model nodes located in Model Layers 1 through 3 (typical depths for agricultural, municipal, industrial, and domestic pumping in the basin). The spatial distribution and magnitudes of these groundwater fluxes were derived from the surface water budget calculations, as detailed in the Agricultural Surface Water Budget and Urban Water Budget sections below.

Agricultural Surface Water Budget. An important component of the successful operation of REDFEM is computation of transient agricultural surface water budget. These water budget components were estimated by using a variety of spatial information, including land use, cropping patterns, irrigation water source, surface water availability in different year types and locations, and the spatial distribution of precipitation. Surface water budget components include groundwater recharge from precipitation, and applied water and agricultural pumping.

Agricultural surface water budgets were developed by intersecting available land use data developed by DWR with the groundwater model grid to assign land use for each model node. Figure D-6 depicts the water purveyor service areas in the model domain. The resulting intersection provided land use, water purveyor, and water source information for each of the REDFEM nodes.

The Integrated Water Flow Model Demand Calculator (DWR, 2011) developed by DWR's Bay-Delta Office and PRISM data were used to simulate root-zone processes and calculate the monthly applied water demand and the monthly groundwater recharge from applied water. The rate of groundwater recharge and the source water (applied water versus precipitation) depends on the season (month) and the availability of water from each source. Attachment D1 contains a technical memorandum (MBK Engineers, 2010) describing the process of estimating the relevant components of the agricultural surface water budget.

Some areas of the domain 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 monthly surface water availability determined the fraction of applied-water demand met from surface water and groundwater. To estimate available surface water in these areas, additional information on the overlying water district was combined with district water rights and contracts. Any remaining applied-water demand, after consideration of available surface water, would be met by groundwater pumping divided between Model Layer 1 (20 percent), Model Layer 2 (60 percent), and Model Layer 3 (20 percent). Attachment D1 details the methods for computing the monthly groundwater recharge of applied water in agricultural areas and the associated monthly agricultural groundwater pumping rates.

Urban Water Balance. Another important component of the successful operation of REDFEM is computation of transient urban water balance. These water balance components were estimated by using a variety of spatial information including land use, irrigation water source, city and water district water-supply and water-demand records, wastewater disposal methods and records, surface water availability, and ET estimates. Urban water balance components in REDFEM include urban pumping and groundwater recharge from applied water, septic systems, and conveyance losses.

A water-balance accounting model and available historical records were used to estimate monthly groundwater recharge in urban areas. Figure D-7 presents a schematic overview of the urban water balance components considered in these calculations. When possible, monthly municipal and water district records were relied on for calculations. Groundwater pumping used for municipal and water district supply was either assigned to the locations of specific city/district wells in Model Layers 2 (50 percent) and 3 (50 percent), or to the overall water district area in Model Layers 1 (80 percent) and 2 (20 percent), in cases where groundwater was supplied by domestic wells.

Seepage from the ACID Canal. Monthly seepage rates were specified to surface nodes in the model along the ACID main canal. Seepage from the ACID canal system is estimated at approximately 44,000 acre-feet per year (CH2M HILL, 2001). Along the main canal, approximately 30,000 acre-feet per year of seepage were prescribed to surface nodes. The remaining 14,000 acre-feet per year of canal seepage was applied across the ACID service area, representing seepage from laterals of the main canal. Groundwater recharge from seepage in the main canal was distributed monthly from April through October. It was assumed that the groundwater recharge generated by canal operations declines over the course of the irrigation season, such that the recharge during each subsequent month was 83 percent of the previous month's canal seepage. This monthly decrease in canal seepage (between April and October) simulates the effects of wetting the fine-grained soils and the decrease in the permeability of the canal bottom during the agricultural season, resulting in less monthly seepage during the agricultural season. Seepage from canal laterals was applied through the year according to agricultural water demands.

6.4.3 No-flow Boundaries

A no-flow boundary was simulated along the margins of the model domain to simulate the lateral extent of freshwater-bearing sediments in the Redding Groundwater Basin. A no-flow boundary was also specified for the bottom boundary of the model, representing the bedrock contact of the Chico Formation.

7.0 Model Calibration

This section describes the approach used to calibrate REDFEM and the results of the calibration process. REDFEM was calibrated by first performing a steady-state calibration to average hydrologic conditions and then performing a transient calibration to data from a selected historical hydrologic period. Calibration was performed by making adjustments to the model construction both manually and by using PEST autocalibration software (Doherty, 2004 and 2010).

7.1 Steady-state Calibration

During the development of REDFEM, a detailed transient agricultural groundwater balance was quantified monthly from January 1999 through December 2008, a 10-year period for which groundwater usage data from districts and municipalities were most plentiful. The groundwater balance components for this period were averaged, and the model was calibrated to average groundwater levels that were measured at selected monitoring wells during the 10-year period.

7.1.1 Steady-state Calibration Targets

The averages of groundwater elevations measured during calendar years (CY) 1999 through 2008 at 67 selected monitoring wells were used as steady-state calibration targets. Figure D-8 depicts the calibration target well locations.

During the calibration process, it was discovered that many reference point elevations at monitoring well locations were not derived from accurate surveying methods, and could have been estimated by using approximate well locations and contour lines on USGS topographic maps. Groundwater elevations are calculated by subtracting the recorded depth-to-water measurements from the reference point elevations, so an unreliable reference point elevation results in the calculation of unreliable groundwater elevations. Groundwater elevation data for calibration target wells were identified as less reliable by comparing them to USGS topographic data and noting large mismatches, or by noting unlikely characteristics (such as four wells 300 feet apart in sloping terrain with the exact same reference point elevation). Of the 67 wells used for calibration, 26 were identified as having less reliable reference point elevations, leaving 41 wells with more reliable reference point elevations (see Figure D-8). Groundwater-level data, computed using the less reliable reference point elevations, were still used for calibration to short- and long-term trends in groundwater levels; however, the absolute groundwater levels computed from the less reliable reference point elevations were not used for calibration adjustment decisions.

7.1.2 Adjustments Made during Calibration

During the calibration process, the following parameters were adjusted to obtain an acceptable degree of calibration:

- Groundwater recharge from precipitation and applied water
- Horizontal and vertical hydraulic conductivity
- Streambed permeability

7.1.3 Steady-state Calibration Results

One way to illustrate the state of calibration using steady-state calibration targets is to develop a scattergram that plots the simulated versus the target groundwater elevation at each calibration well. Figure D-9 presents results for the 41 calibration wells with more reliable reference point elevations. A perfect fit between simulated and target groundwater elevations would plot along a 1:1 correlation line. As shown on Figure D-9, the simulated groundwater levels show good agreement with target groundwater levels. This implies that REDFEM provides accurate estimates of the steady-state groundwater elevations and flow directions in the vicinities of calibration target wells.

The calculation of the root mean squared error (RMSE) divided by the range of target groundwater elevations (Range) is another commonly used measure of calibration. As a rule of thumb, a well-calibrated regional model will have an RMSE to Range ratio (RMSE/Range) of less than 10 percent. The RMSE/Range of the steady-state calibration presented herein is 4.1 percent, well below the 10 percent criterion.

The gain in streamflow from baseflow in the Sacramento River between Keswick Reservoir and the outflow location at the south end of the Redding Groundwater Basin is estimated at approximately 700,000 acre-feet per year (CH2M HILL, 2001). Although REDFEM does not explicitly simulate streamflow, the gain in streamflow from baseflow (groundwater discharge to the stream) is estimated by adding the groundwater discharges to drain and wadi boundary condition nodes, and subtracting the stream seepage from the wadi boundary condition nodes. This combined net groundwater discharge to streams and drainages in the steady-state model is approximately 679,000 acre-feet per year, which is within 2.5 percent of the target value of 700,000 acre-feet per year. This close match indicates that the overall simulated groundwater balance is reasonable with regard to basin-scale groundwater recharge and discharge. Table D-1 summarizes the magnitudes of the groundwater balance components derived from the steady-state calibration.

TABLE D-1
Average Annual REDFEM Groundwater Balance Summary: Calendar Years 1999 through 2008
Documentation of the Redding Groundwater Basin Finite-Element Model

Groundwater Balance Component	1,000 acre-feet
Groundwater Recharge	
Groundwater Recharge from Precipitation	685
Groundwater Recharge from Applied Water (Agricultural)	59
Groundwater Recharge from Applied Water (Urban)	15
Groundwater Recharge from the ACID Main Canal	30
Groundwater Recharge from Streams	22
Total Groundwater Recharge	**811**
Groundwater Discharge	
Agricultural Groundwater Pumping	34
Urban Groundwater Pumping	41
Groundwater Discharge to Streams and Drainages	701
Groundwater Loss to ET	35
Total Groundwater Discharge	**811**

7.2 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 consistent with the CY 1999-2008 averaging period used for the steady-state calibration. This period was selected because it is a period when groundwater usage data from districts and municipalities were most plentiful.

The parameters adjusted during the transient calibration process were the aquifer storage properties. The magnitude of fluctuation in groundwater levels was reviewed after adjustment during each calibration simulation. An initial specific storage estimate for Model Layers 2 through 4 remained unchanged from the initial value of $2.0\text{x}10^{-6}$ per foot. An initial specific yield estimate of 0.1 was reduced to 0.08 near the Redding Municipal Airport and in the southwestern portion of the model.

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 target groundwater levels for each measurement recorded throughout the 10-year calibration period (CY 1999-2008). Figure D-10 shows the results of this comparison for all 835 groundwater-level measurements used in the transient calibration process for the 41 calibration wells with more reliable reference point elevations. Figure D-10 also presents the statistical parameters associated with this comparison. The R^2

goodness of fit between the simulated and observed values is 0.93, and the RMSE/Range is slightly more than 5 percent. Both of these summary statistics demonstrate that the model provides transient simulated groundwater elevations that closely match target groundwater elevations across the basin and throughout the 10-year calibration period.

The other method used to evaluate the quality of the transient calibration was to compare the simulated time-series groundwater elevations (hydrographs) for each of the 41 calibration monitoring wells that have more reliable reference point elevations. Wells with less reliable reference point elevations were evaluated for the magnitude of groundwater-level trends and fluctuations, as opposed to absolute groundwater levels. Figure D-11 presents the hydrograph comparisons. Figure D-8 depicts calibration wells with less reliable reference point elevations. Although some significant deviations remain between simulated and target groundwater levels during certain periods and at some well locations, REDFEM generally performs well in replicating the absolute groundwater elevations, fluctuations, and transient trends at most calibration monitoring wells.

8.0 Summary and Conclusions

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

The REDFEM grid has an approximate 500-foot spatial resolution in areas where the proposed project is being considered, and REDFEM is composed of four vertically integrated model layers. Model Layer 1 (uppermost model layer) was assigned a uniform thickness of 50 feet below the water table to assess impacts on streams, riparian habitat, and wetlands. The thicknesses of Model Layers 2 and 3 of 100 and 200 feet, respectively, were selected to represent typical groundwater production zones within the basin. The thickness of Model Layer 4 represents the deeper portion of the freshwater aquifer system down to the Chico Formation, which has not typically been used as a source of groundwater.

The surface water balance, including agricultural and urban pumping, and groundwater recharge from 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 basis. Areal groundwater recharge and pumping fluxes are independently computed for each node in the model. Surface stream stages were defined using available data, including USGS topographic maps and stream gage elevations, and assumed to be constant throughout the course of the model simulations.

REDFEM was calibrated to both steady-state and transient groundwater elevation data sets. Groundwater elevations recorded during CY 1999-2008 were used as transient calibration targets, and averages for that period were used as steady-state calibration targets. More qualitative calibration targets such as the magnitude of the water balance components and the pattern and magnitude of surface water and groundwater interaction were also considered.

REDFEM is a valuable analytical tool to estimate the effects of groundwater pumping on both groundwater levels and changes in surface water and groundwater interaction within the Redding Groundwater Basin.

9.0 References

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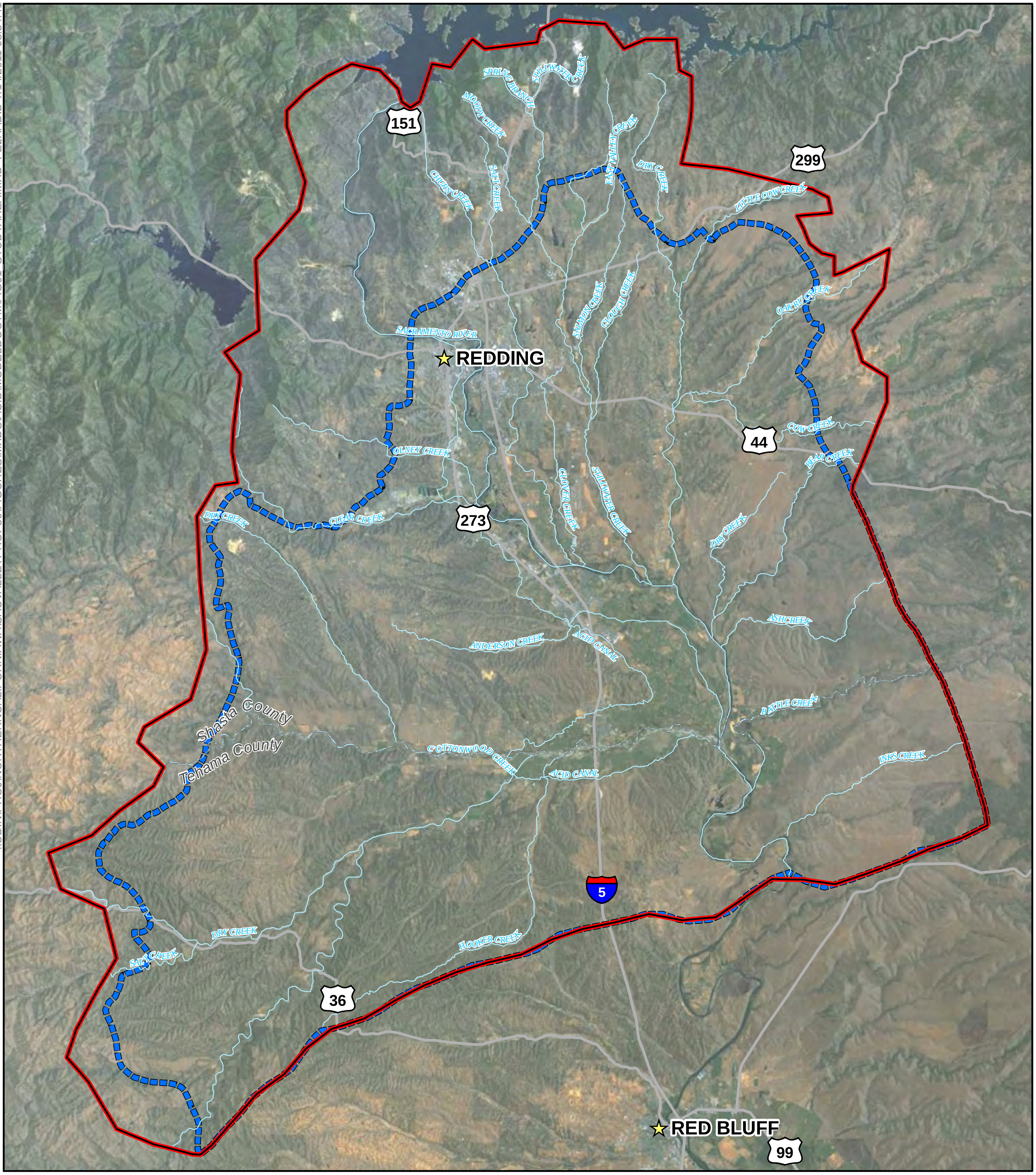
Figures



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LEGEND

- STUDY AREA AND REDFEM BOUNDARY
- REDDING GROUNDWATER BASIN BOUNDARY

N

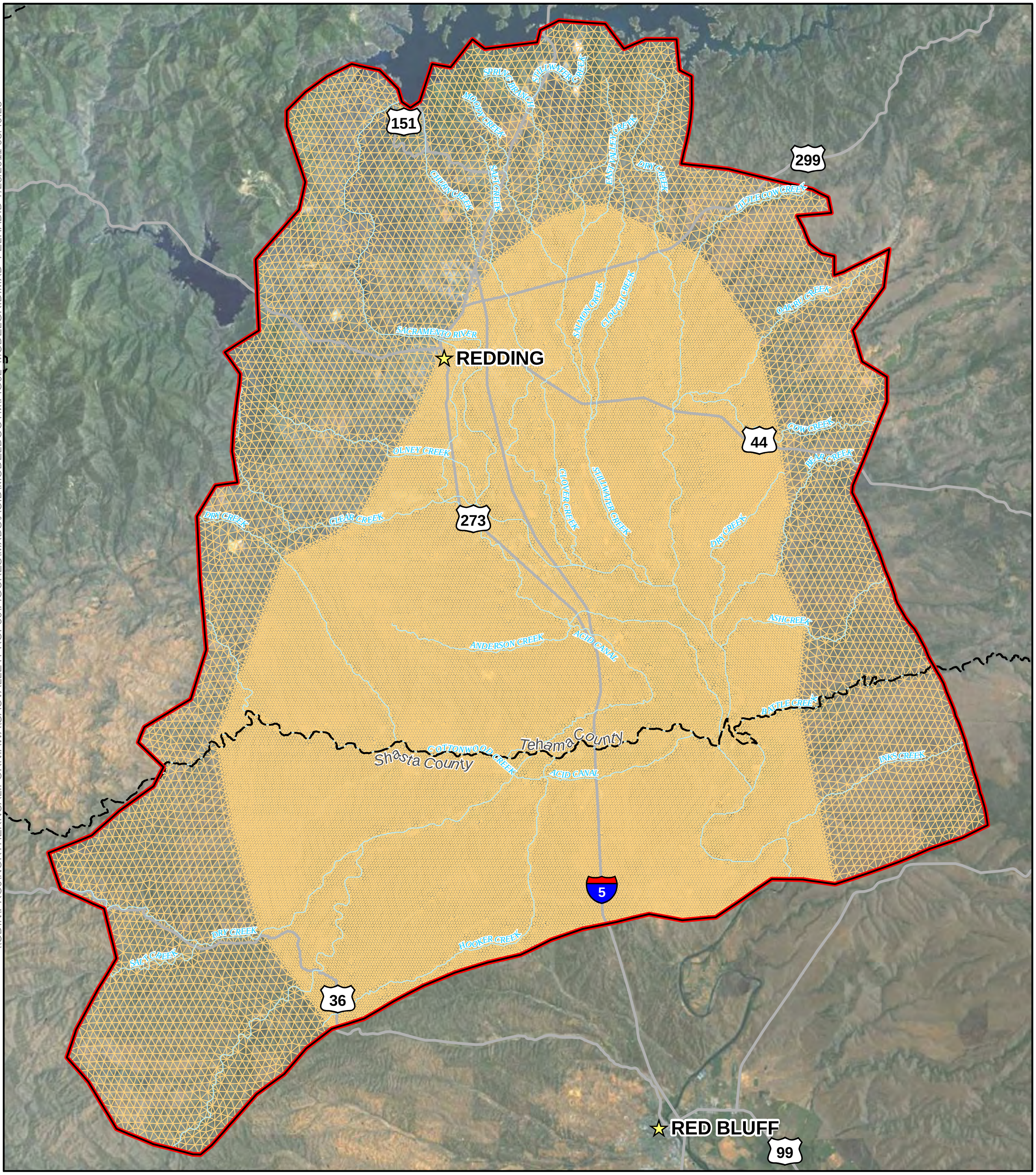
0 5 10 Miles

NOTE:

SOURCE OF AERIAL PHOTOGRAPH, ESRI, 2011.

FIGURE D-1
LOCATIONS OF THE REDDING GROUNDWATER BASIN AND THE STUDY AREA
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

CH2MHILL



LEGEND

STUDY AREA AND REDFEM BOUNDARY

REDFEM GRID

0 5 10 Miles

N

NOTE:

SOURCE OF AERIAL PHOTOGRAPH, ESRI, 2011.

FIGURE D-2
REDFEM GRID
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

CH2MHILL

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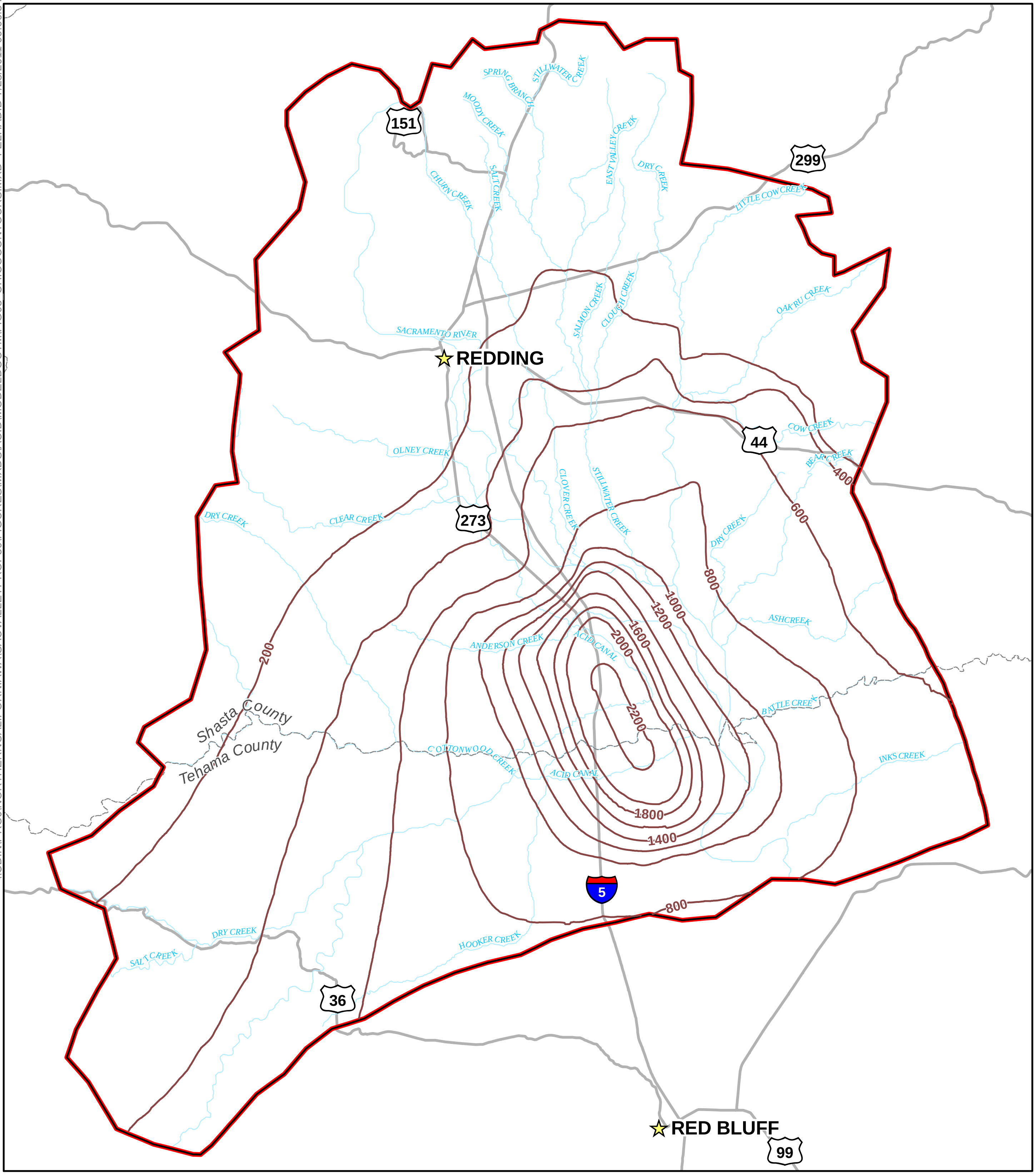


LEGEND

STUDY AREA AND REDFEM BOUNDARY

DEPTH TO TOP OF CHICO FORMATION CONTOUR (feet)

0 5 10 Miles

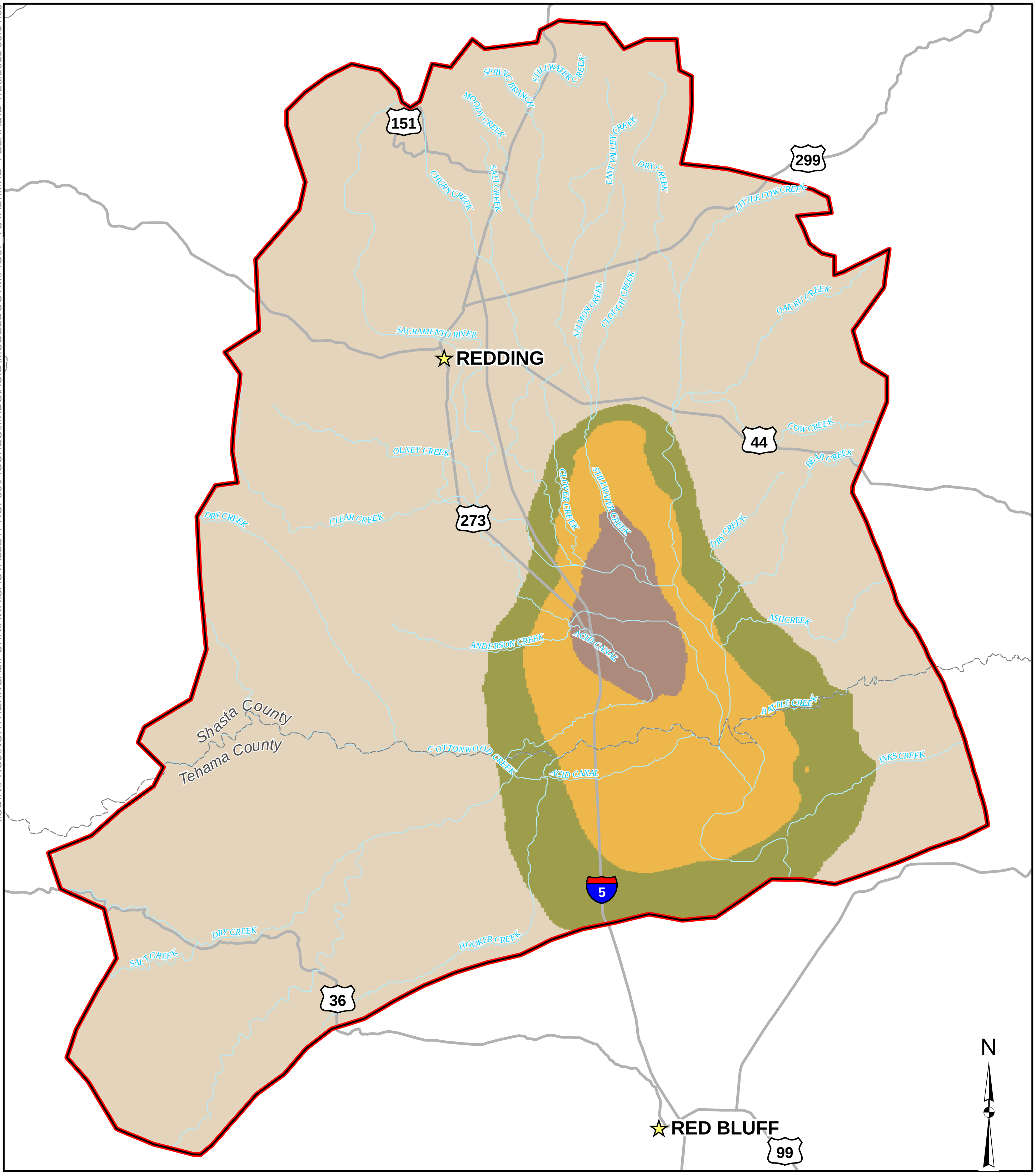
N

NOTE:

MODIFIED FROM BULLETIN 74-8 (DWR, 1968).

FIGURE D-3
DEPTH TO TOP OF CHICO FORMATION
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

CH2MHILL



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LEGEND

STUDY AREA AND REDFEM BOUNDARY

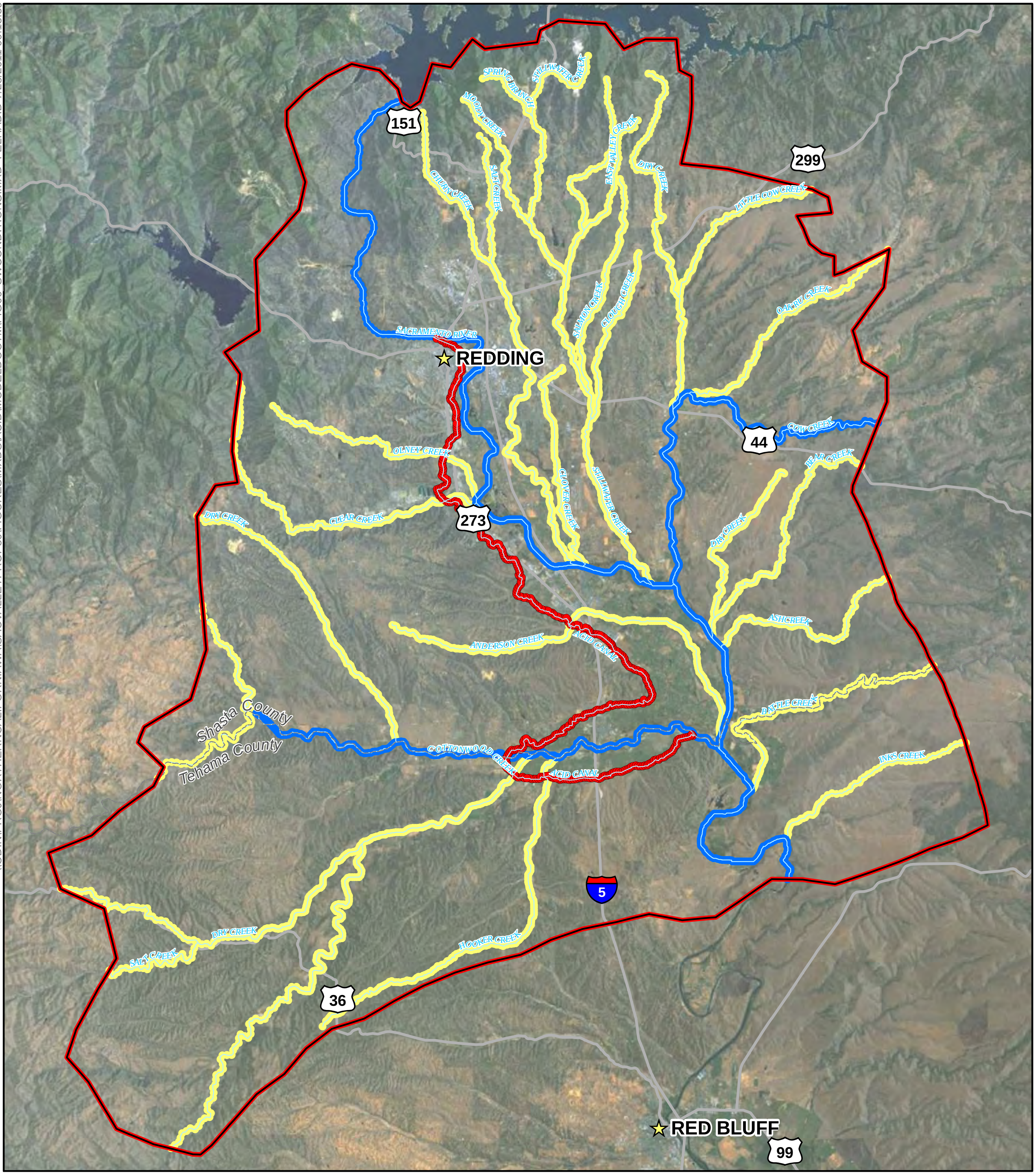
TOTAL TRANSMISSIVITY (feet²/day)

- < 50,000
- 50,000 to 100,000
- 100,000 to 250,000
- >250,000

0 5 10 Miles

FIGURE D-4
REDFEM TRANSMISSIVITY DISTRIBUTION
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

CH2MHILL



LEGEND

STUDY AREA AND REDFEM BOUNDARY

BOUDARY CONDITION TYPE

- ONE-WAY HEAD-DEPENDANT FLUX (DRAIN)
- TWO-WAY HEAD-DEPENDANT FLUX (WADI)
- SPECIFIED FLUX

0 5 10 Miles

N

NOTE:

SOURCE OF AERIAL PHOTOGRAPH, ESRI, 2011.

FIGURE D-5
BOUNDARY CONDITIONS ASSOCIATED WITH STREAMS AND CANALS
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

CH2MHILL

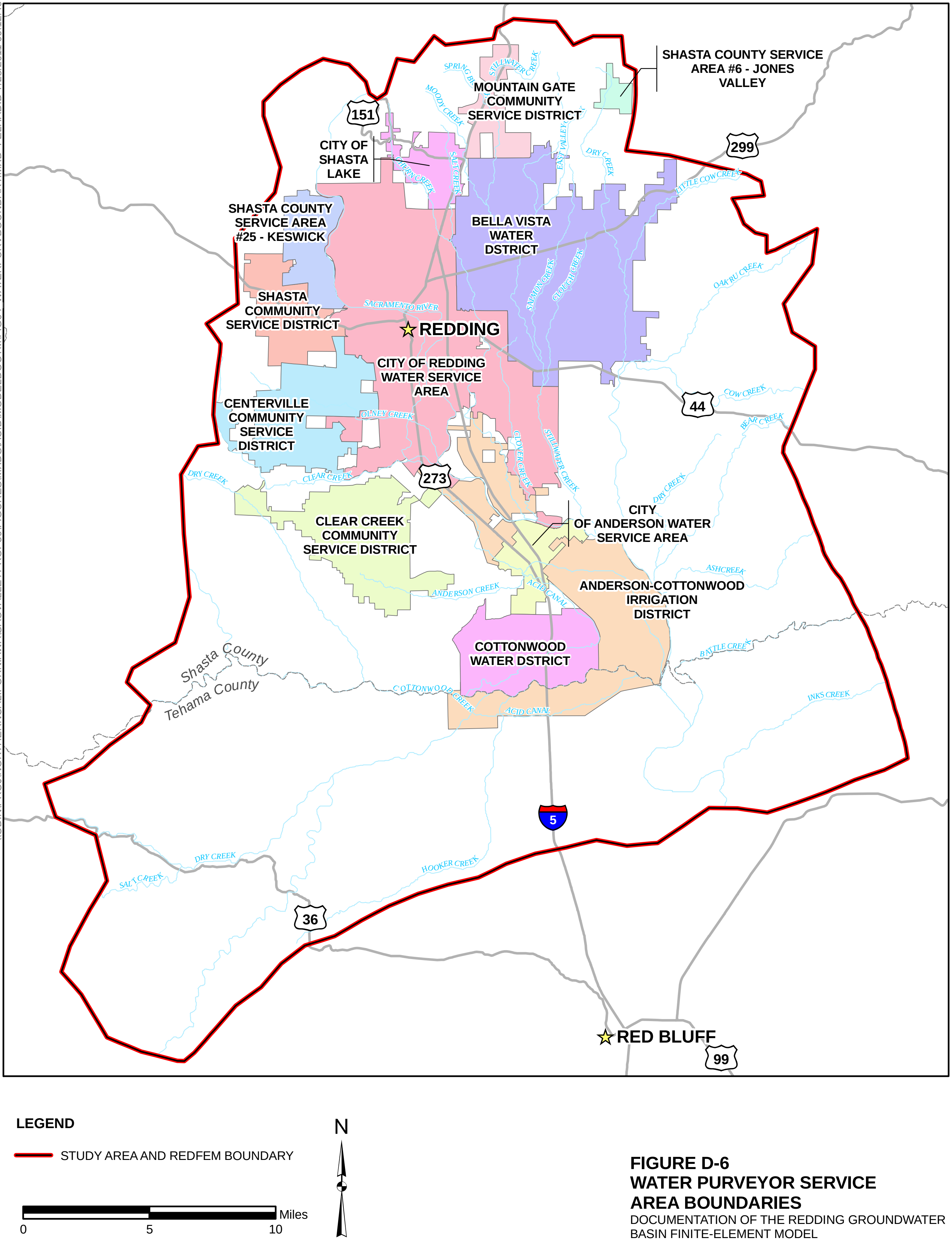
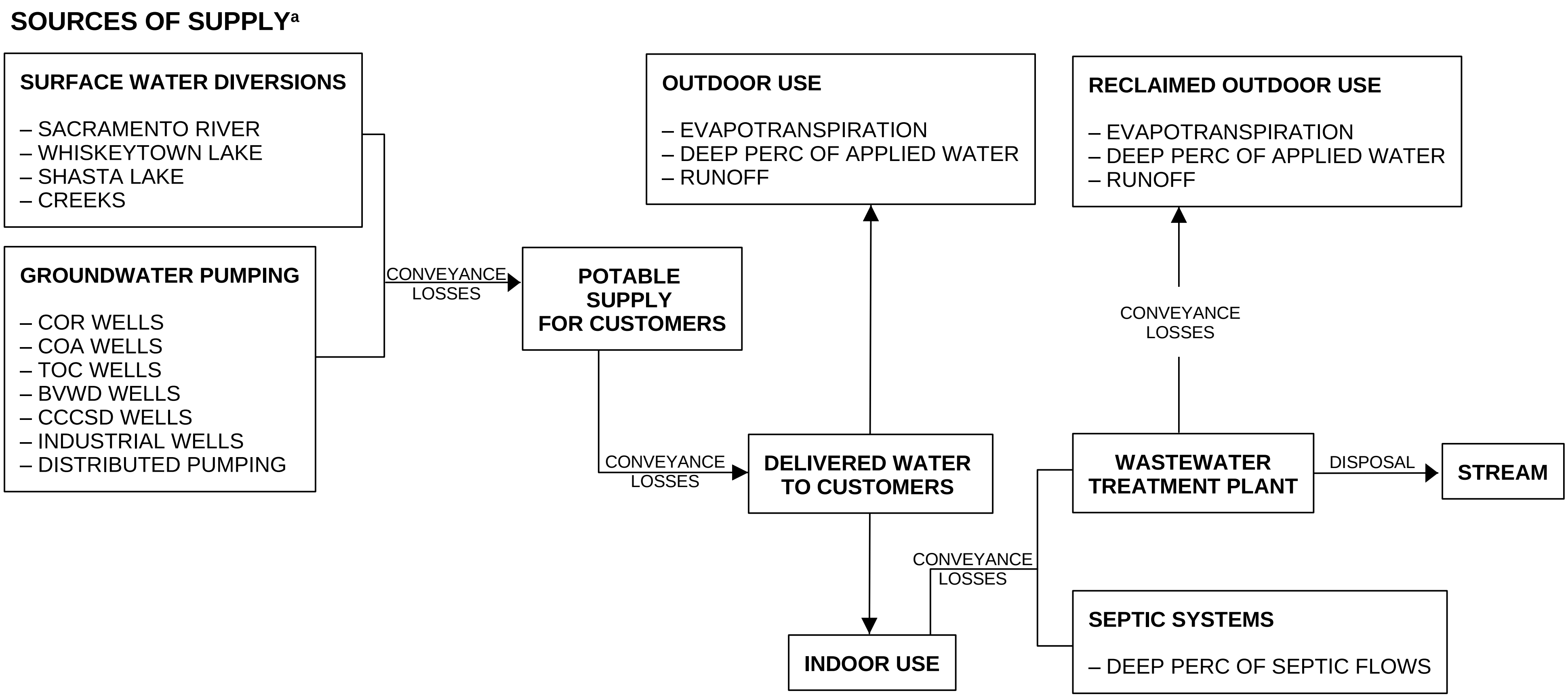


FIGURE D-6
WATER PURVEYOR SERVICE AREA BOUNDARIES
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

CH2MHILL



[a]RECLAIMED WATER IS ALSO A MINOR SOURCE OF SUPPLY AND IS SHOWN AFTER THE WASTEWATER TREATMENT PLANT BOX IN THIS SCHEMATIC.

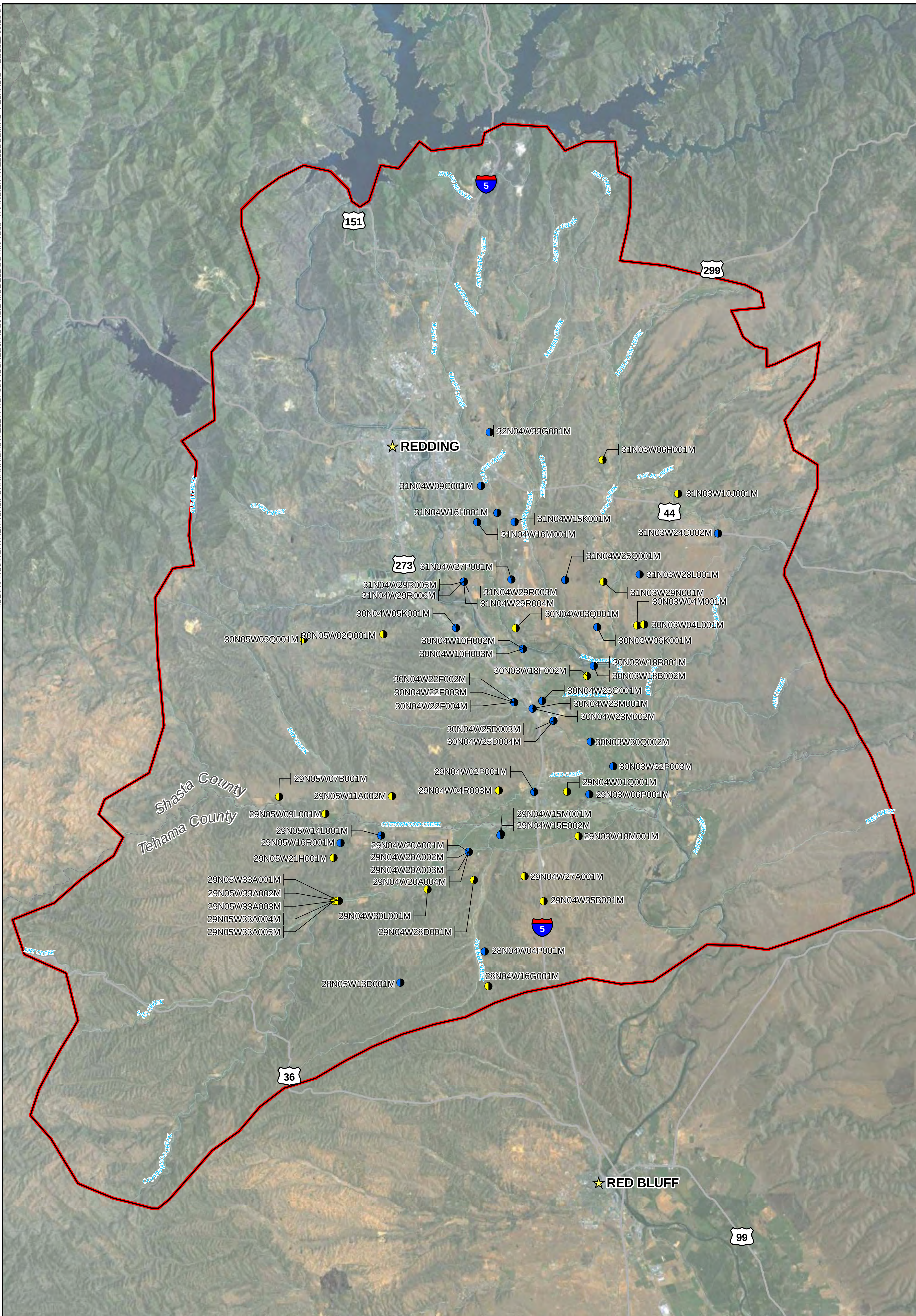
NOTES:

COR = CITY OF REDDING
COA = CITY OF ANDERSON
TOC = TOWN OF COTTONWOOD
BVWD = BELLA VISTA WATER DISTRICT
CCCSD = CLEAR CREEK COMMUNITY SERVICES DISTRICT

FIGURE D-7
REDDING BASIN URBAN WATER BUDGET COMPONENTS
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

CH2MHILL

FIG07_WaterBudget.grf



LEGEND

STUDY AREA AND REDFEM BOUNDARY

CALIBRATION TARGET WELL

MONITORING WELL WITH MORE RELIABLE REFERENCE ELEVATION

MONITORING WELL WITH LESS RELIABLE REFERENCE ELEVATION

0 3.5 7 Miles

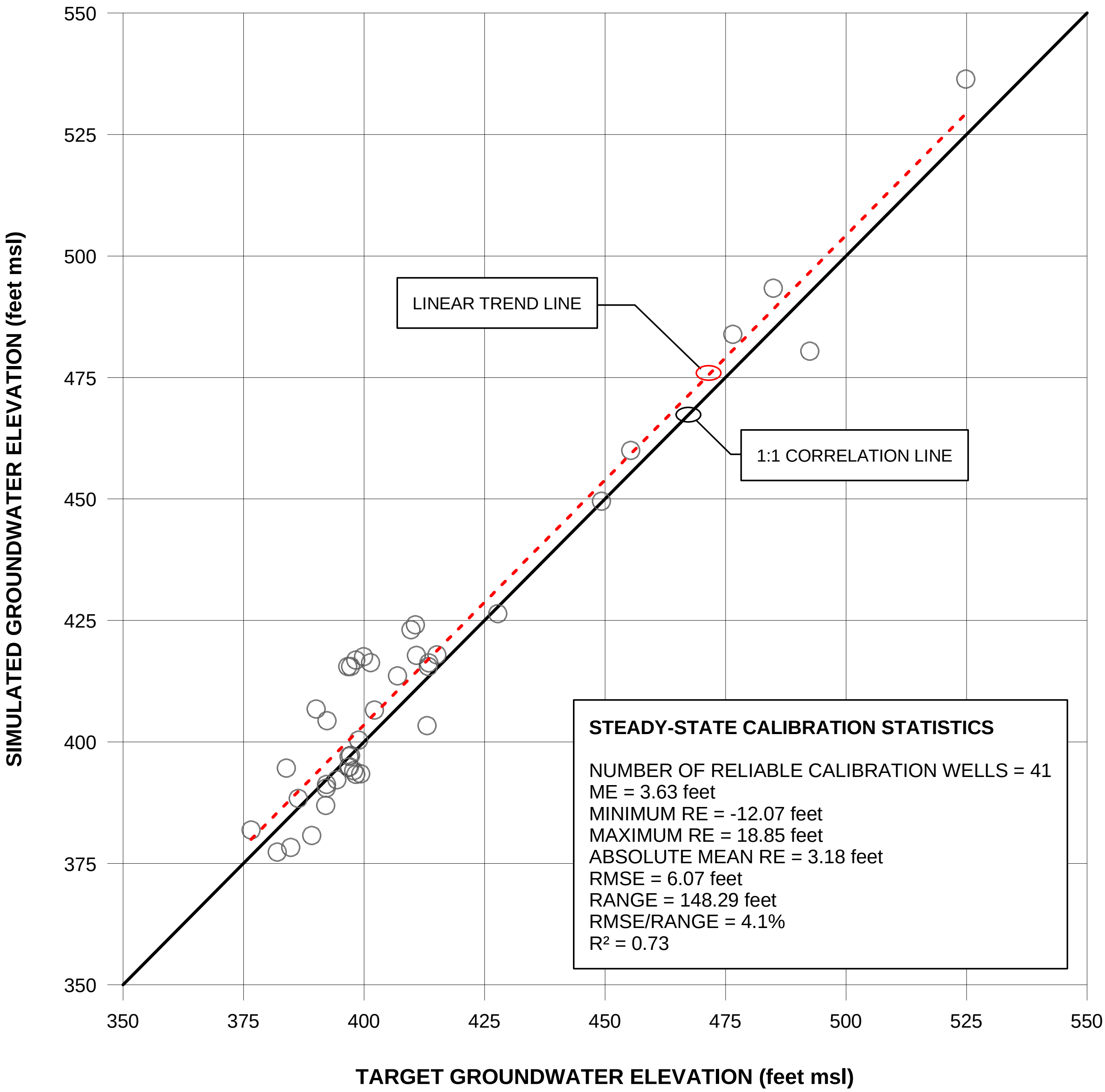
N

NOTE:

SOURCE OF AERIAL PHOTOGRAPH, ESRI, 2011.

FIGURE D-8
LOCATION OF CALIBRATION TARGET WELLS
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

CH2MHILL



NOTES:

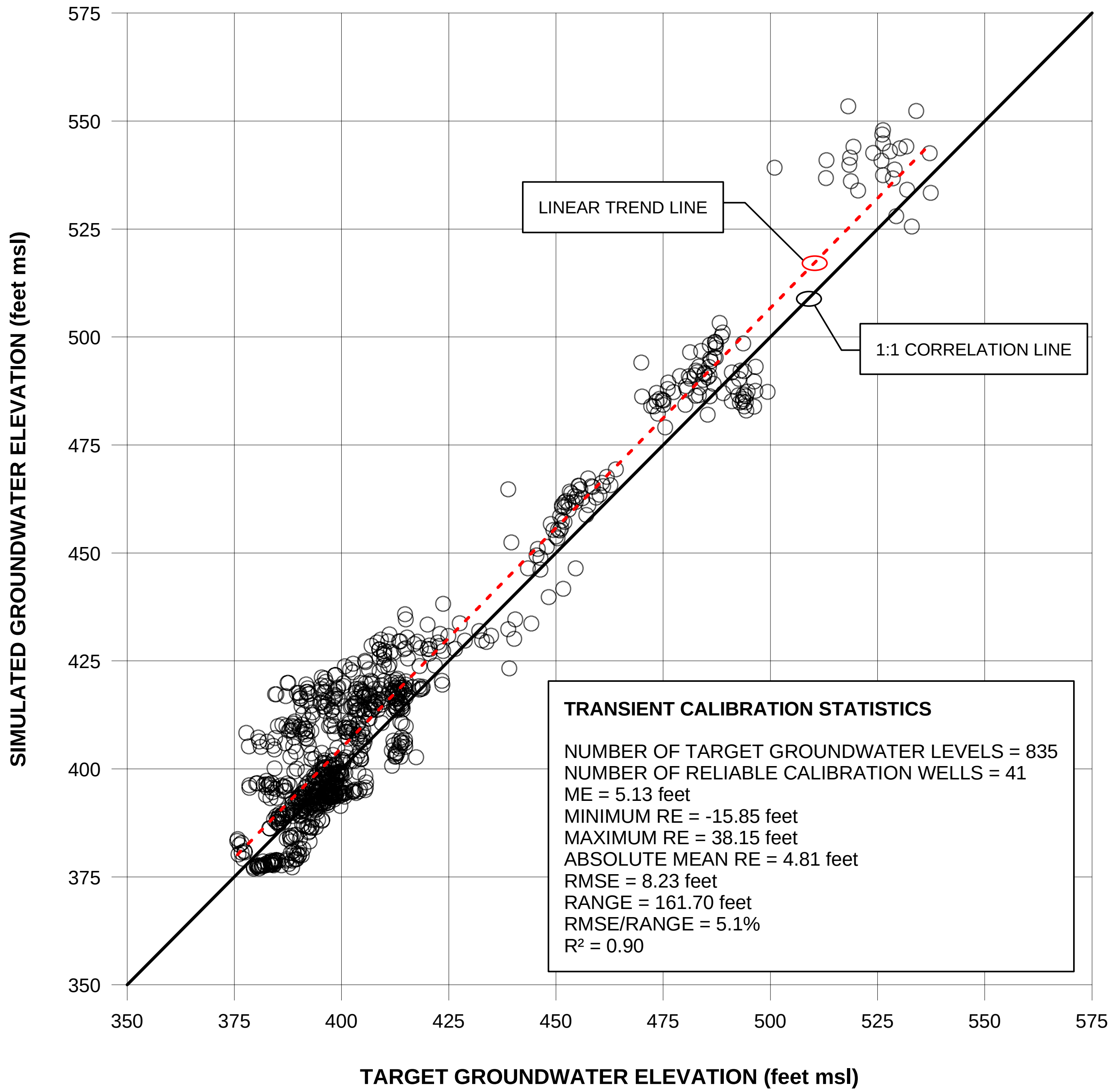
TARGET GROUNDWATER ELEVATION COMPUTED AS THE AVERAGE OF AVAILABLE GROUNDWATER LEVEL DATA FOR A GIVEN CALIBRATION WELL OVER THE CALENDAR YEARS 1999 THROUGH 2008.

ME = MEAN RESIDUAL ERROR
MSL = MEAN SEA LEVEL
RE = RESIDUAL ERROR
RMSE = ROOT MEAN SQUARE ERROR
RANGE = RANGE IN TARGET GROUNDWATER LEVELS
R^2 = SQUARE OF THE CORRELATION COEFFICIENT

FIGURE D-9
REDFEM STEADY-STATE CALIBRATION SCATTERGRAM
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

CH2MHILL

FIG09_Obs_Sim.grf

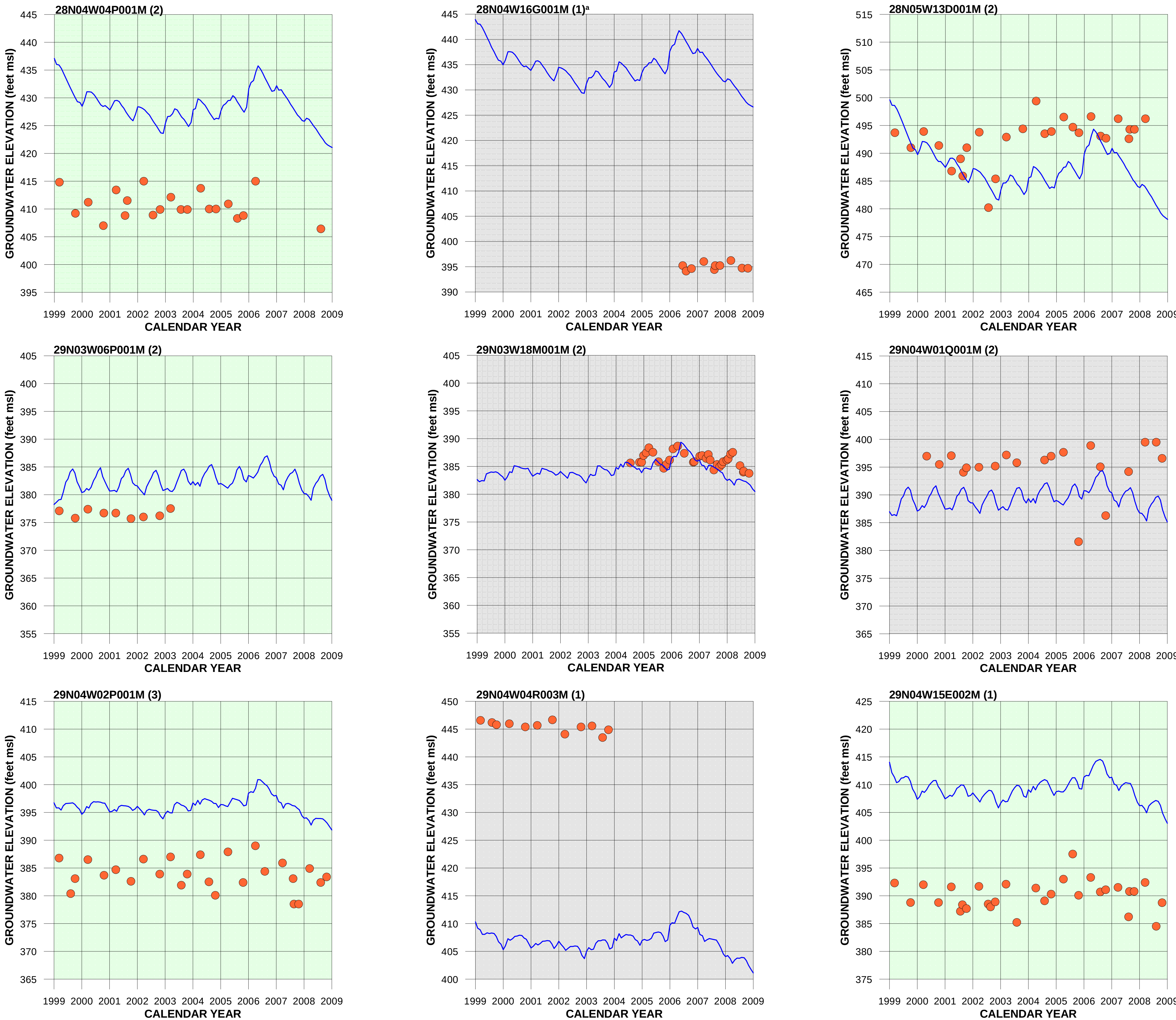


NOTES:

TARGET GROUNDWATER ELEVATION COMPUTED AS THE AVERAGE OF AVAILABLE GROUNDWATER LEVEL DATA FOR A GIVEN CALIBRATION WELL OVER THE CALENDAR YEARS 1999 THROUGH 2008.

ME = MEAN RESIDUAL ERROR
MSL = MEAN SEA LEVEL
RE = RESIDUAL ERROR
RMSE = ROOT MEAN SQUARE ERROR
RANGE = RANGE IN TARGET GROUNDWATER LEVELS
R^2 = SQUARE OF THE CORRELATION COEFFICIENT

FIGURE D-10
REDFEM TRANSIENT CALIBRATION SCATTERGRAM
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL



LEGEND

- TARGET GROUNDWATER ELEVATION (feet msl)
- SIMULATED GROUNDWATER ELEVATION (feet msl)
- MONITORING WELL WITH MORE RELIABLE REFERENCE POINT ELEVATION
- MONITORING WELL WITH LESS RELIABLE REFERENCE POINT ELEVATION

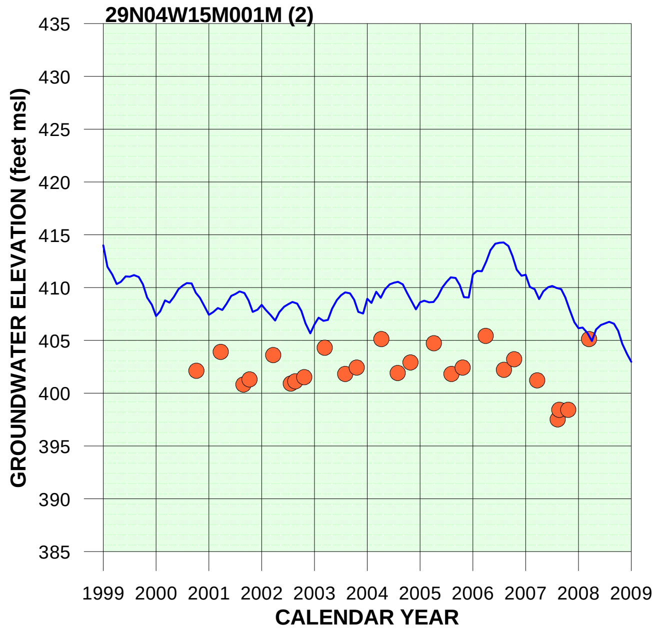
[a]THE RANGE IN Y-AXIS VALUES ON THIS PLOT IS GREATER THAN 50 FEET.

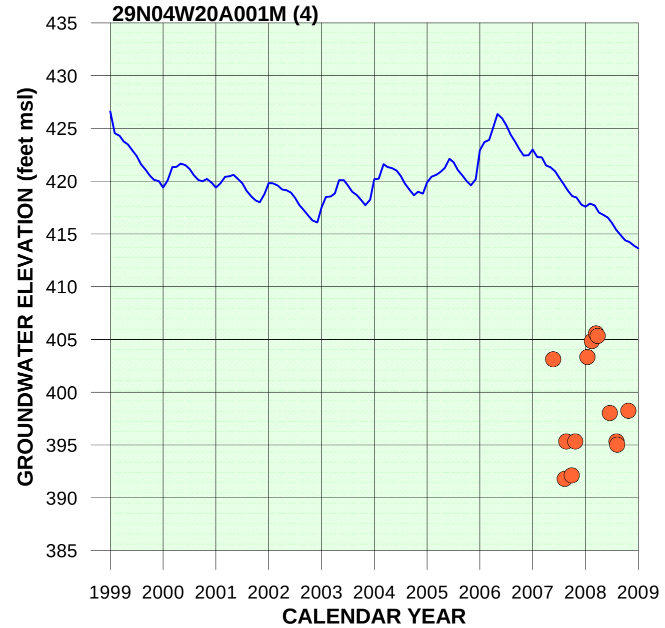
NOTES:

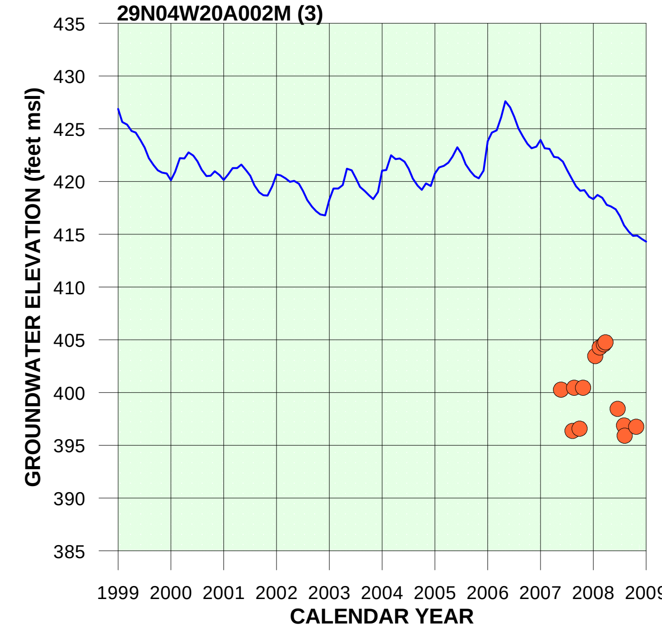
THE VALUE PROVIDED IN PARENTHESIS AFTER THE STATE WELL NUMBER INDICATES THE MODEL LAYER ASSOCIATED WITH THE WELL.

THE STANDARDIZED RANGE IN Y-AXIS VALUES ON EACH PLOT IS 50 FEET, UNLESS OTHERWISE NOTED.

FIGURE D-11 (PAGE 1 OF 8)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL







LEGEND

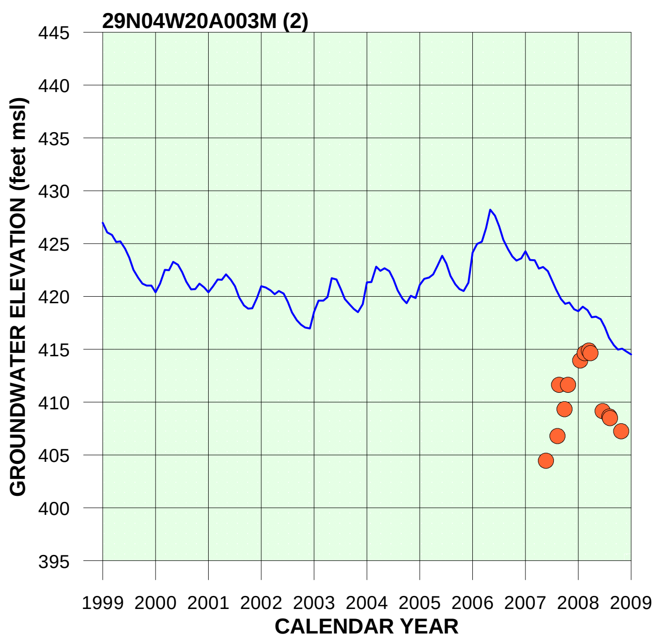
- TARGET GROUNDWATER ELEVATION (feet msl)
- SIMULATED GROUNDWATER ELEVATION (feet msl)
- MONITORING WELL WITH MORE RELIABLE REFERENCE POINT ELEVATION
- MONITORING WELL WITH LESS RELIABLE REFERENCE POINT ELEVATION

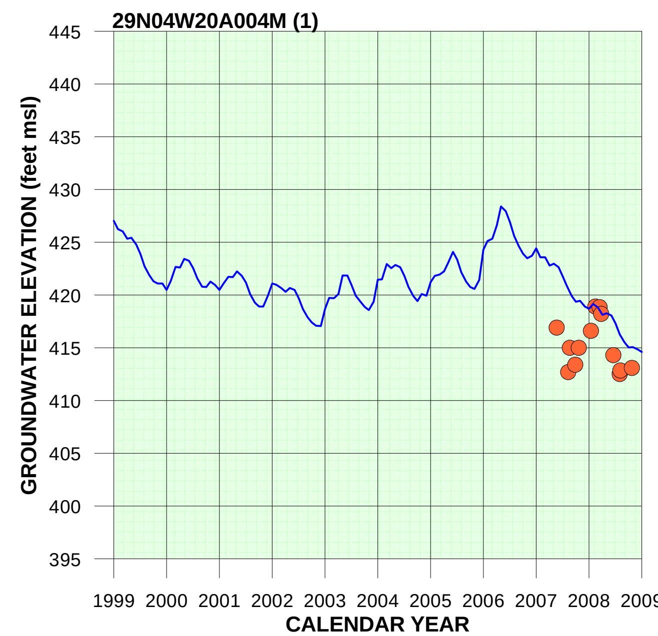
[a]THE RANGE IN Y-AXIS VALUES ON THIS PLOT IS GREATER THAN 50 FEET.

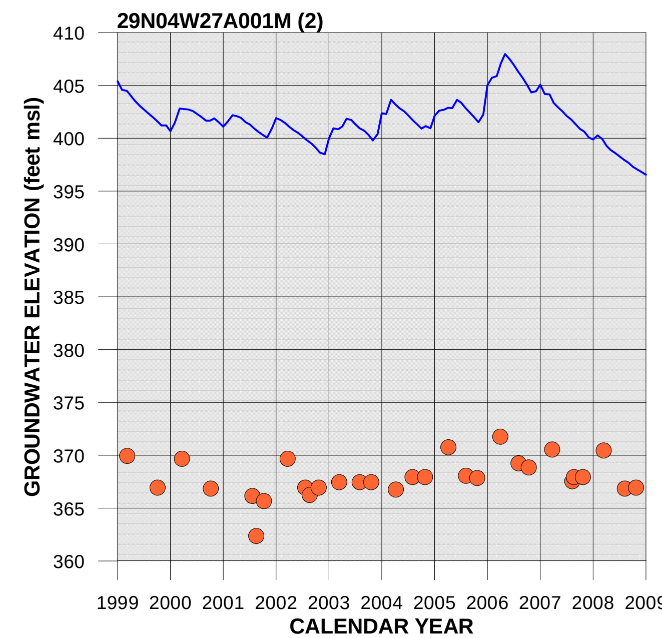
NOTES:

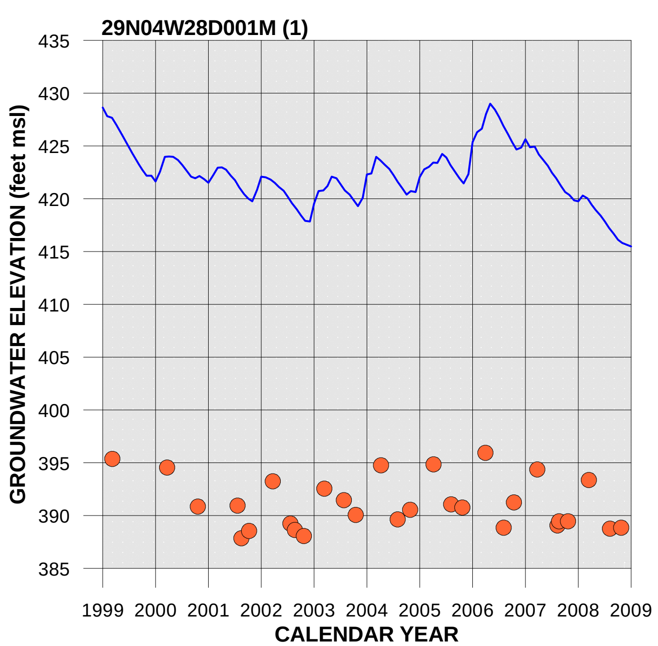
THE VALUE PROVIDED IN PARENTHESIS AFTER THE STATE WELL NUMBER INDICATES THE MODEL LAYER ASSOCIATED WITH THE WELL.

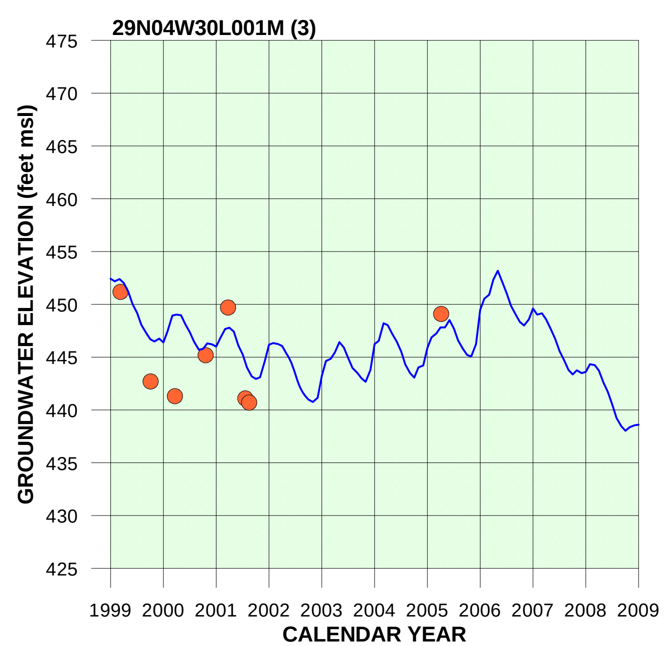
THE STANDARDIZED RANGE IN Y-AXIS VALUES ON EACH PLOT IS 50 FEET, UNLESS OTHERWISE NOTED.











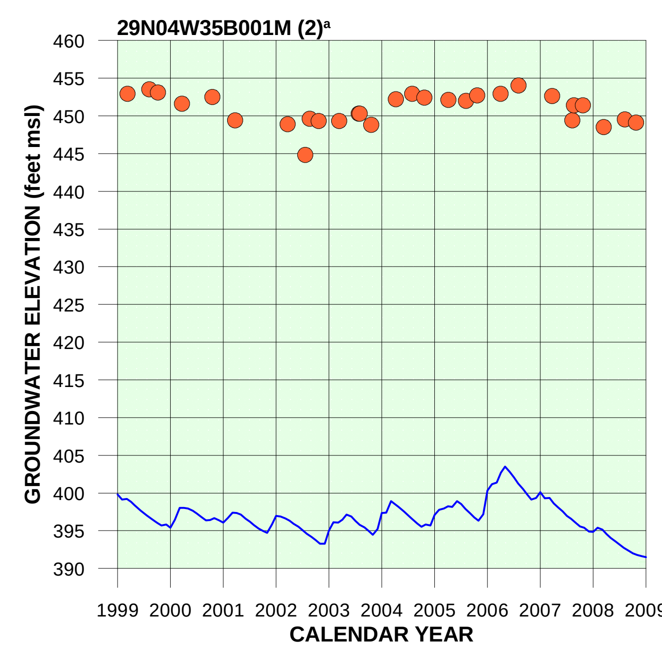
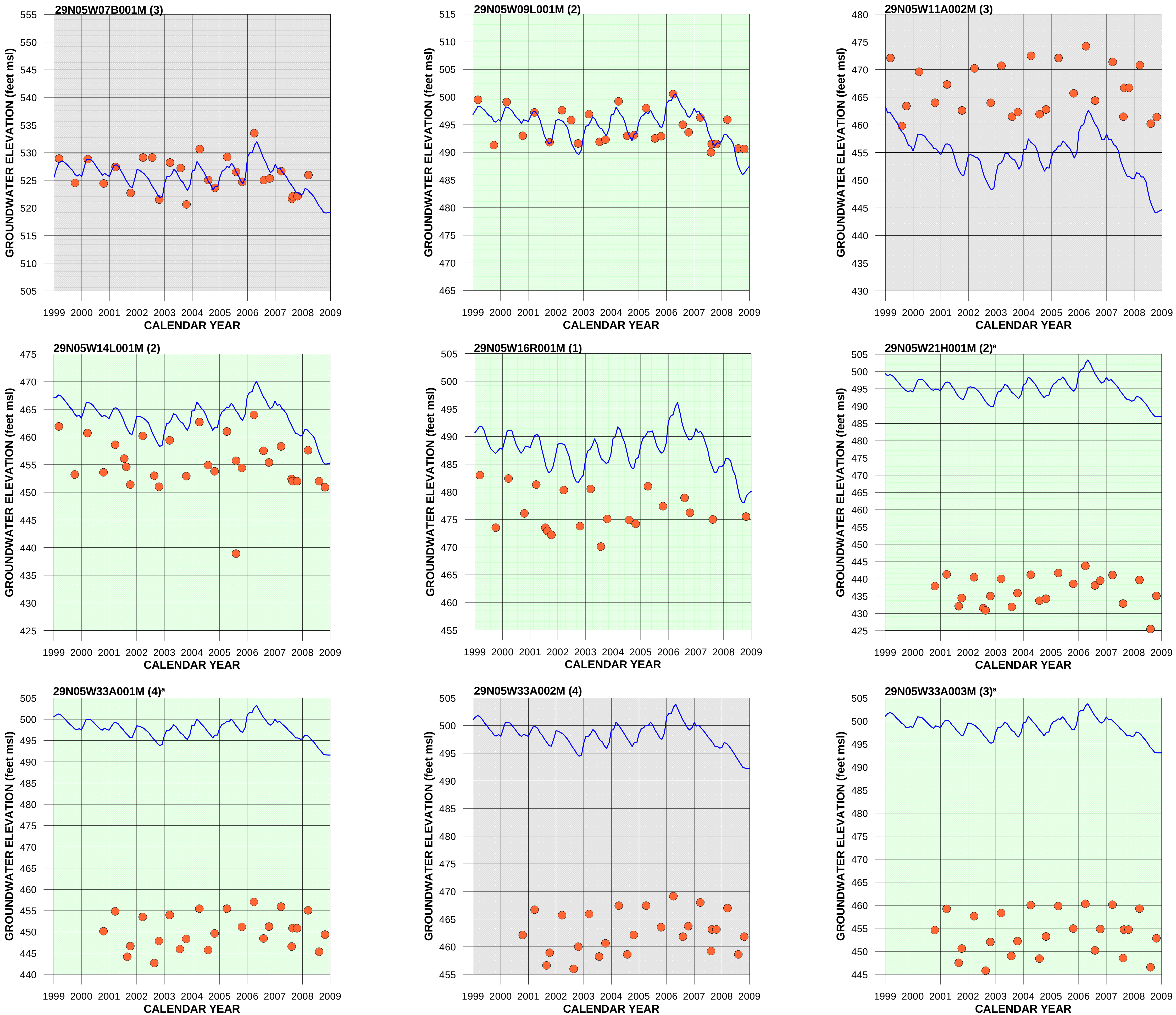


FIGURE D-11 (PAGE 2 OF 8)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL



LEGEND

- TARGET GROUNDWATER ELEVATION (feet msl)
- SIMULATED GROUNDWATER ELEVATION (feet msl)
- MONITORING WELL WITH MORE RELIABLE REFERENCE POINT ELEVATION
- MONITORING WELL WITH LESS RELIABLE REFERENCE POINT ELEVATION

[a]THE RANGE IN Y-AXIS VALUES ON THIS PLOT IS GREATER THAN 50 FEET.

NOTES:

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FIGURE D-11 (PAGE 3 OF 8)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

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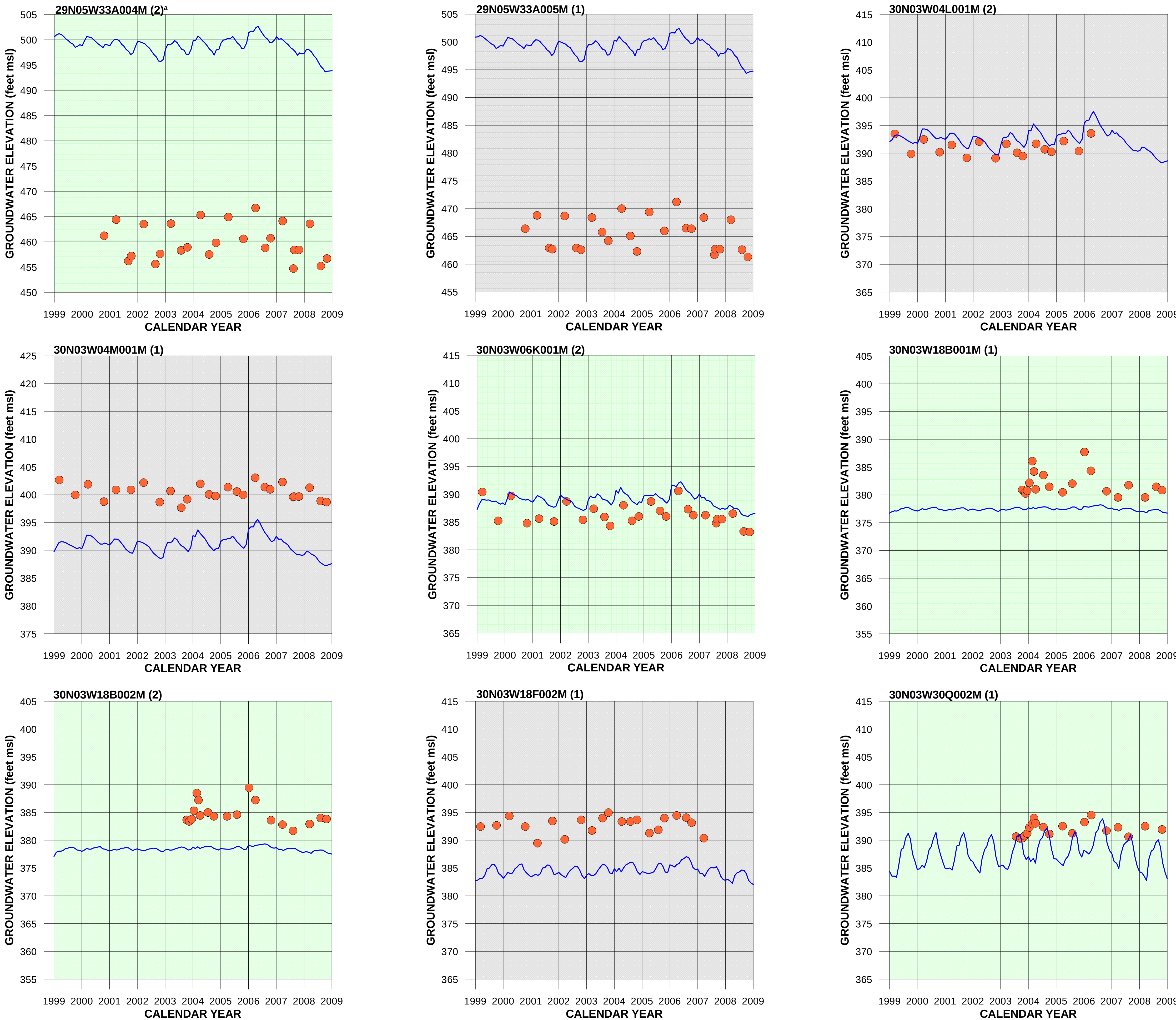

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FIGURE D-11 (PAGE 4 OF 8)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

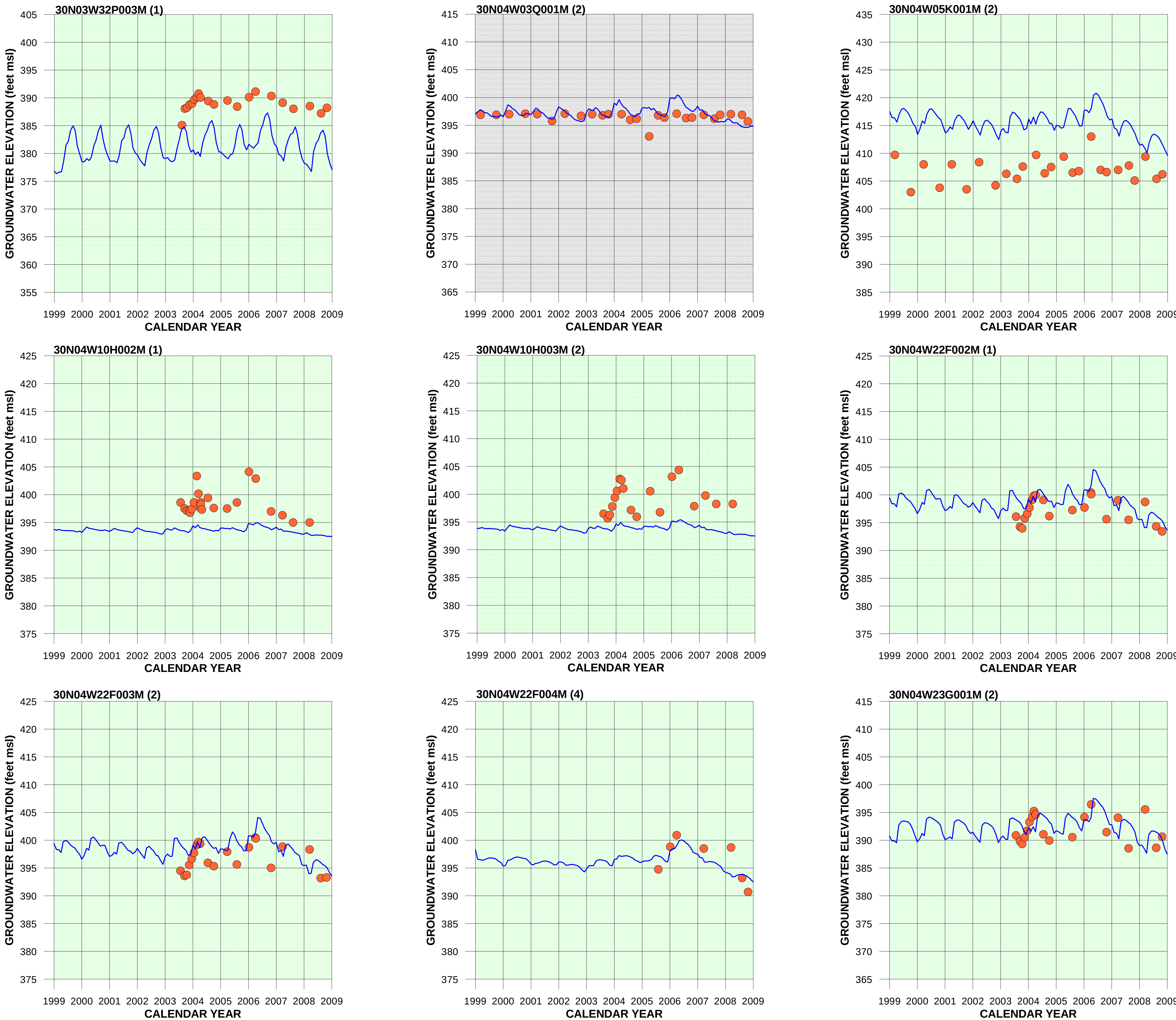

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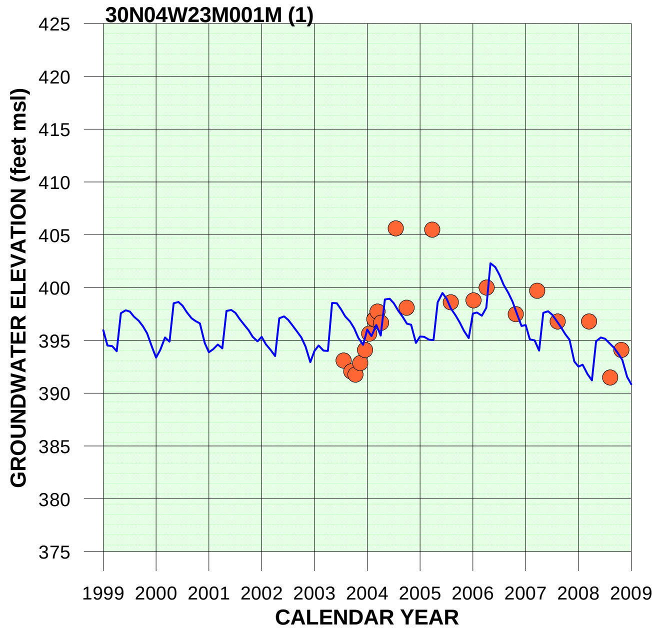
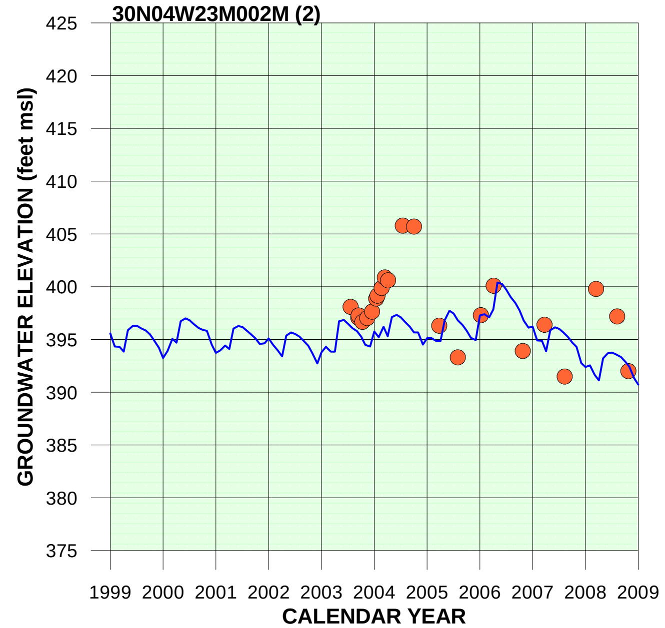
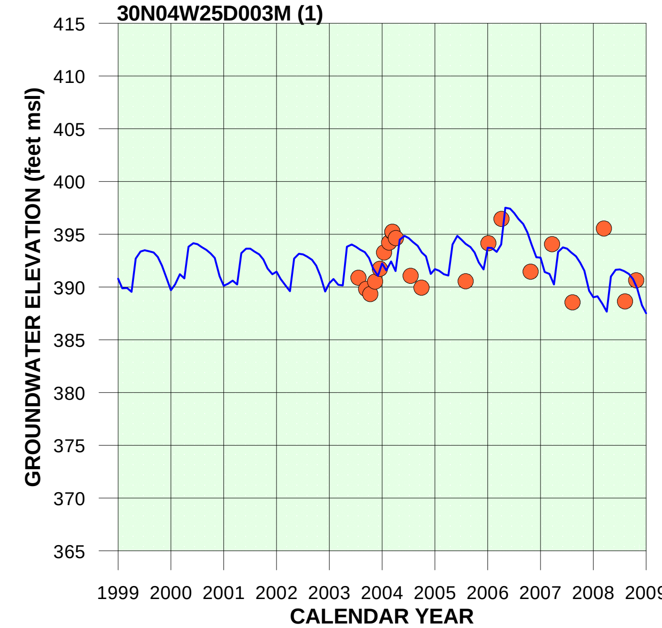
FIGURE D-11 (PAGE 5 OF 8)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

CH2MHILL







LEGEND

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SIMULATED GROUNDWATER ELEVATION (feet msl)

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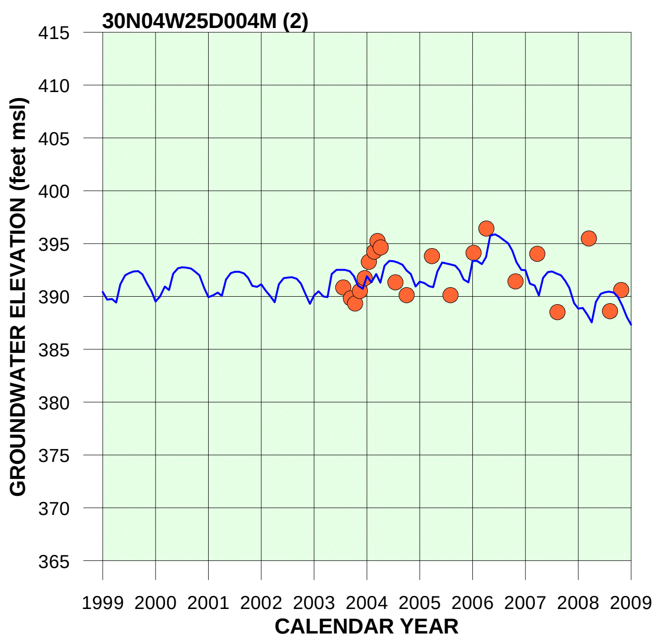

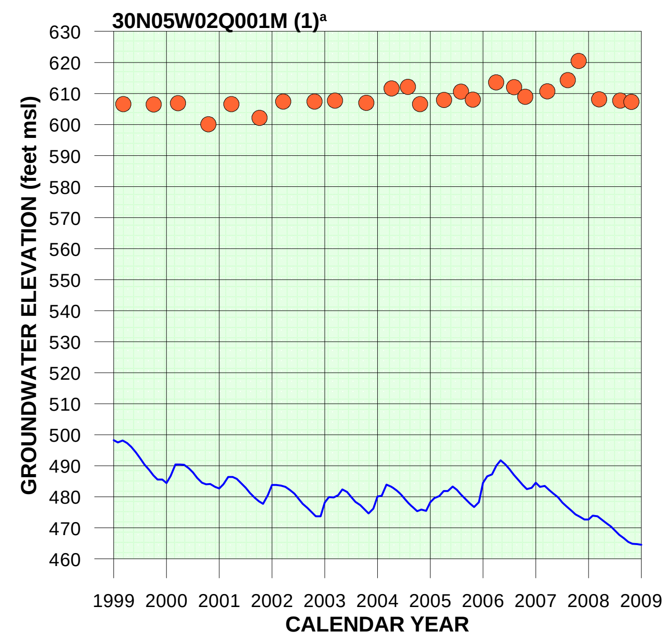

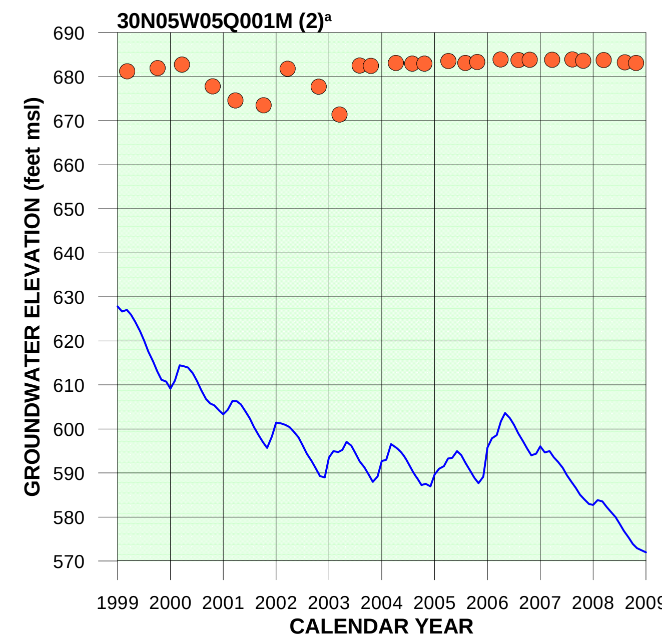

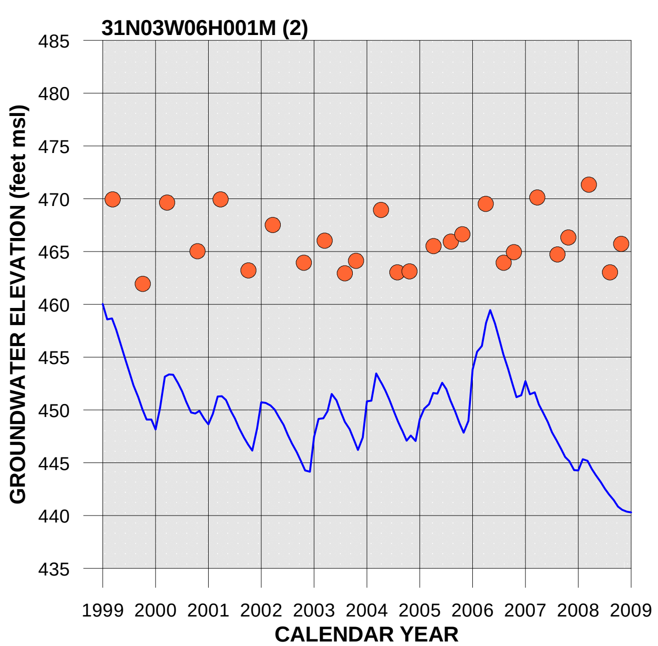

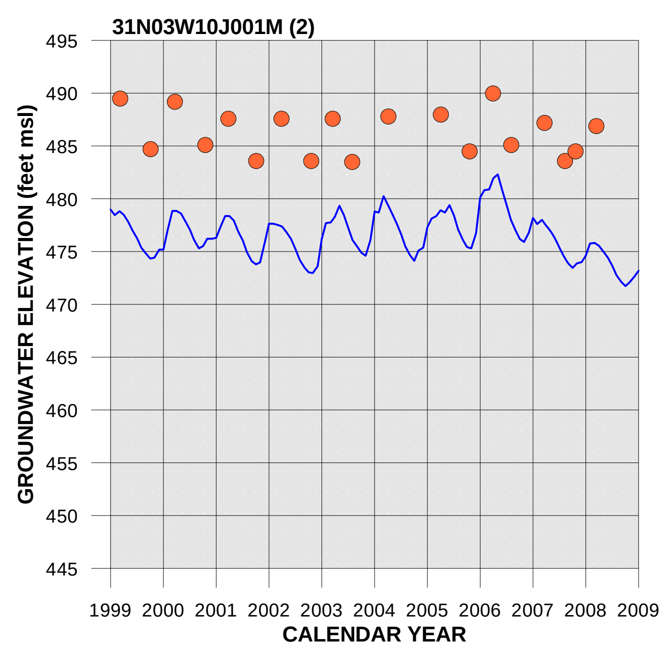

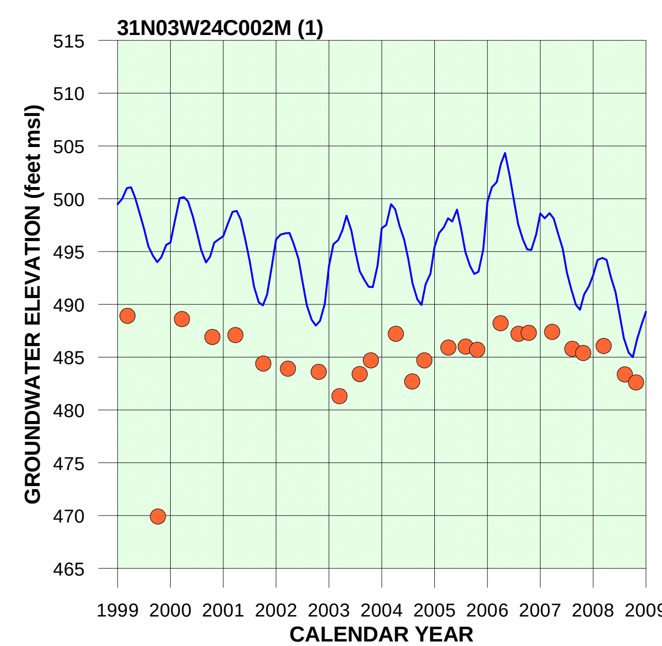

FIGURE D-11 (PAGE 6 OF 8)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

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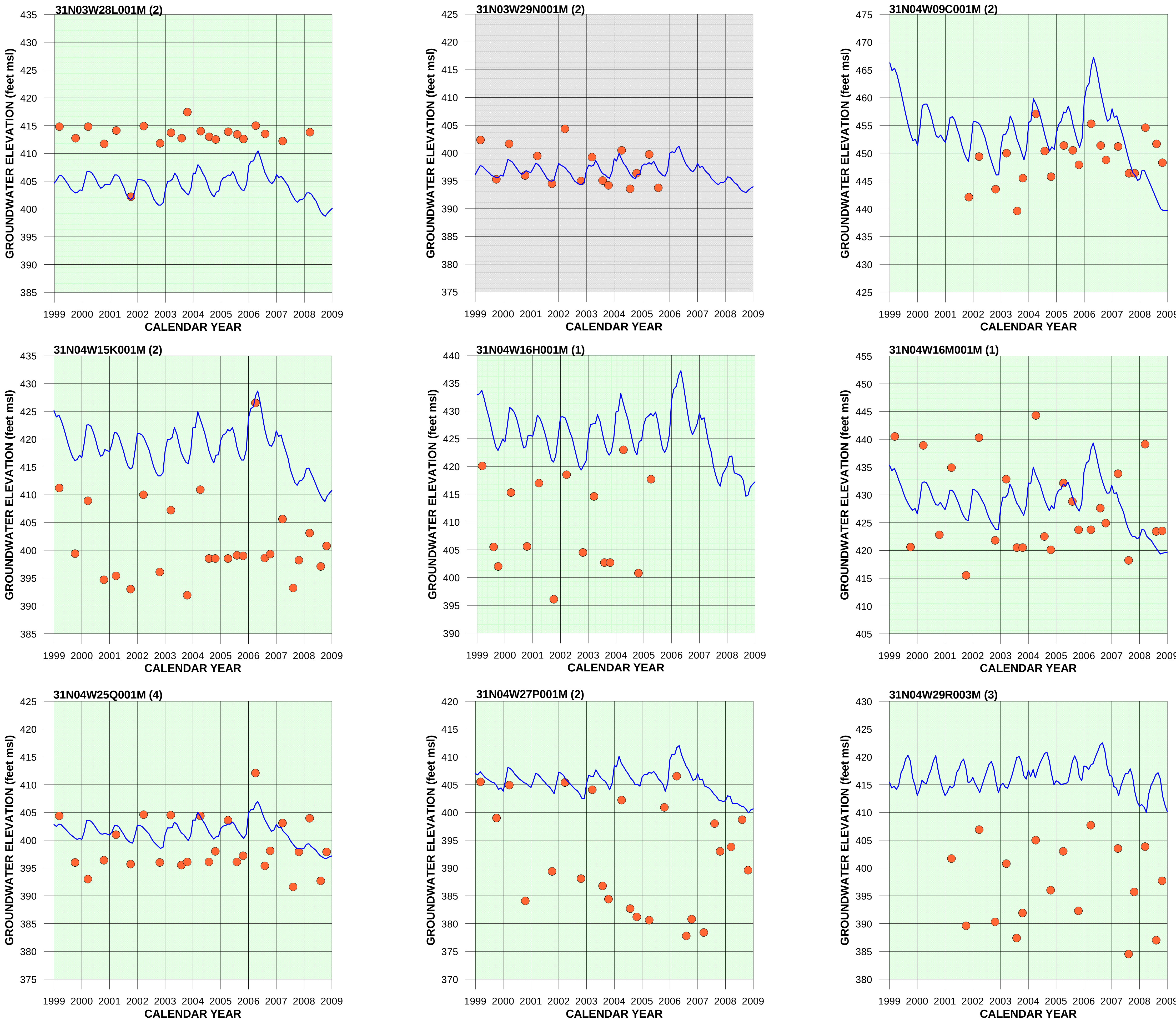

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FIGURE D-11 (PAGE 7 OF 8)
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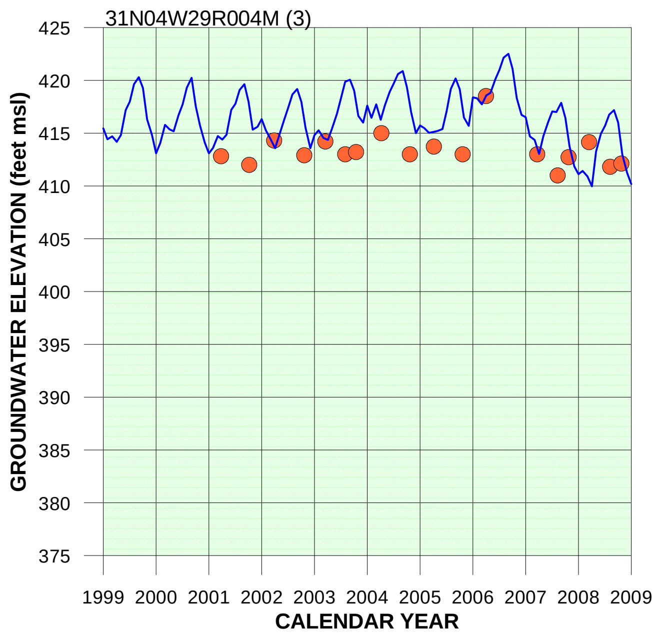
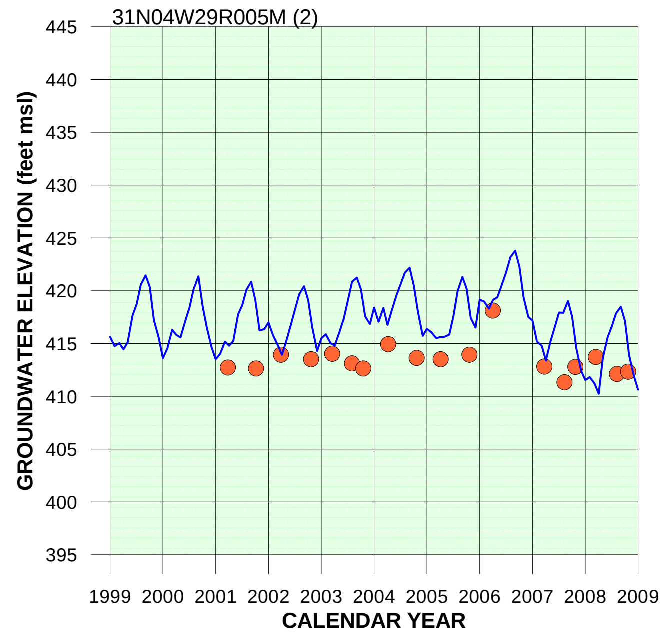
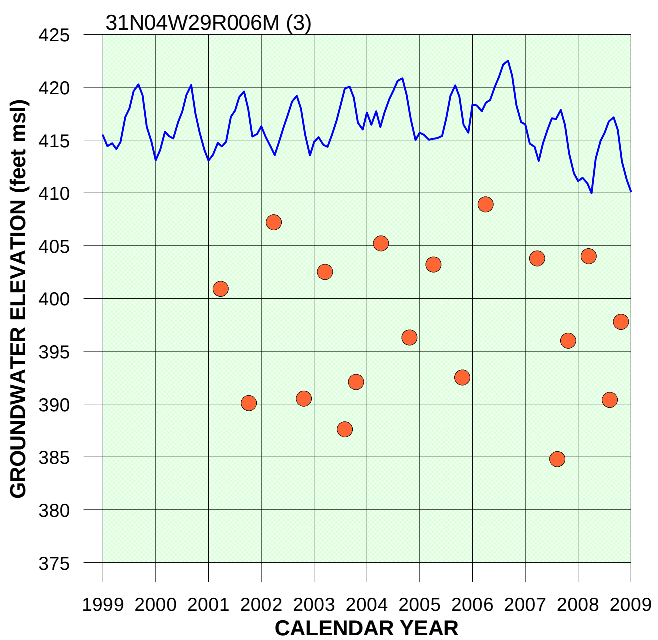
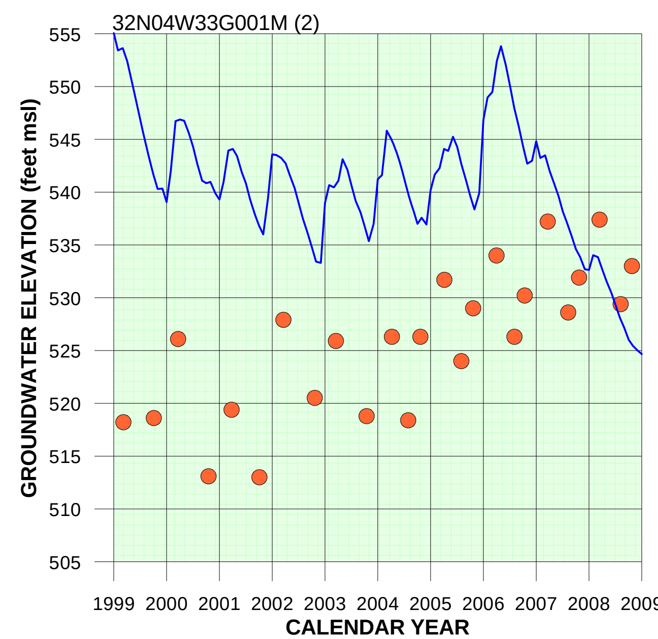
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL









LEGEND

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FIGURE D-11 (PAGE 8 OF 8)
TRANSIENT CALIBRATION HYDROGRAPHS
DOCUMENTATION OF THE REDDING GROUNDWATER BASIN FINITE-ELEMENT MODEL

CH2MHILL

Attachment D1
Redding Basin Water Budget Inputs

TECHNICAL MEMORANDUM

DATE: September 15, 2010

TO: Peter Lawson
Michael Basial
Nate Brown

FROM: Lee G. Bergfeld

SUBJECT: Redding Basin Water Budget Inputs

This technical memorandum documents data and methods used in development of water budget inputs to a MicroFem groundwater model of the Redding Basin. Water budget inputs are time-series of monthly deep percolation, split between deep percolation of applied water and precipitation, and groundwater pumping for each of the 55,938 groundwater model nodes. Inputs described in this memorandum are for agricultural and native vegetation areas within the model domain and do not include urban areas. Water budget inputs were developed for the entire groundwater model simulation period from January 1980 through December 2008.

INPUT DATA

Water budget inputs were developed using a combination of data on land use, soil properties, precipitation, and a root zone soil moisture accounting model, the Integrated Water Flow Model Demand Calculator (IDC) developed the Department of Water Resources (DWR) Bay-Delta Modeling Office. The following sections document the source of this data and provide data summaries for the groundwater model domain.

Land Use Data

Water budgets were developed based on land use for areas contributing to each groundwater model node. Geographic information system (GIS) land use data were developed by Department of Water Resources (DWR) Northern District staff during field surveys conducted in 1999 for Tehama County and 2005 for Shasta County. These data are assumed to represent current level land uses and are constant throughout the simulation period. Table 1 summarizes land use data for the entire model domain by county for three broad land use categories; agricultural, urban, and native vegetation. Land use is further disaggregated within these three broad categories for specific crops and urban uses in the GIS data.

Table 1: Summary of Land Uses within Model Domain (acres)

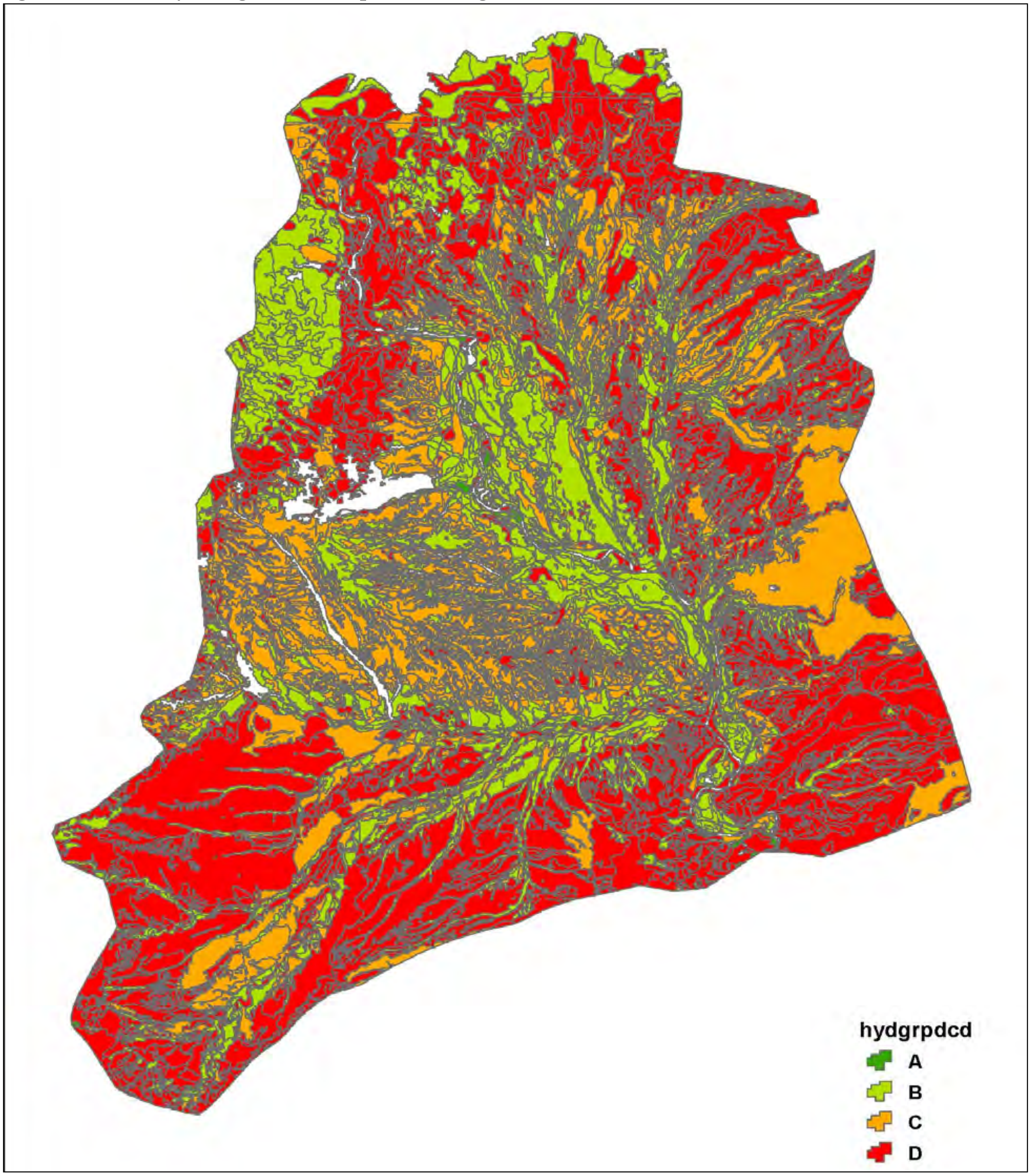
County	Agricultural	Urban	Native Vegetation	Total
Shasta	23,947	87,431	235,417	346,795
Tehama	5,864	2,610	170,992	179,466
Total	29,811	90,041	406,409	526,261

Data presented in Table 1 show approximately 77 percent of lands within the model domain are native vegetation, with 17 percent urban, and the remaining 6 percent in agriculture. Pasture is the primary agricultural land use, accounting for approximately two thirds of all agricultural land use in the model. Other crops include alfalfa, truck crops, grains, field crops, orchards, and vineyards.

Soil Data

Hydrologic soil group (HSG) data was extracted from the Natural Resources Conservation Service (NRCS) SSURGO Version 2.2 database. There are four HSGs; A, B, C, and D. HSGs are used to classify soils based on runoff potential with A soils having the lowest runoff potential and the highest saturated hydraulic conductivity and D soils having the highest runoff potential and lowest saturated hydraulic conductivity. HSG data for the model domain were combined with land use and precipitation data in GIS for use in IDC to estimate deep percolation and applied water demands based on the combination of these inputs.

Figure 1: NRCS Hydrologic Soil Groups in Redding Basin



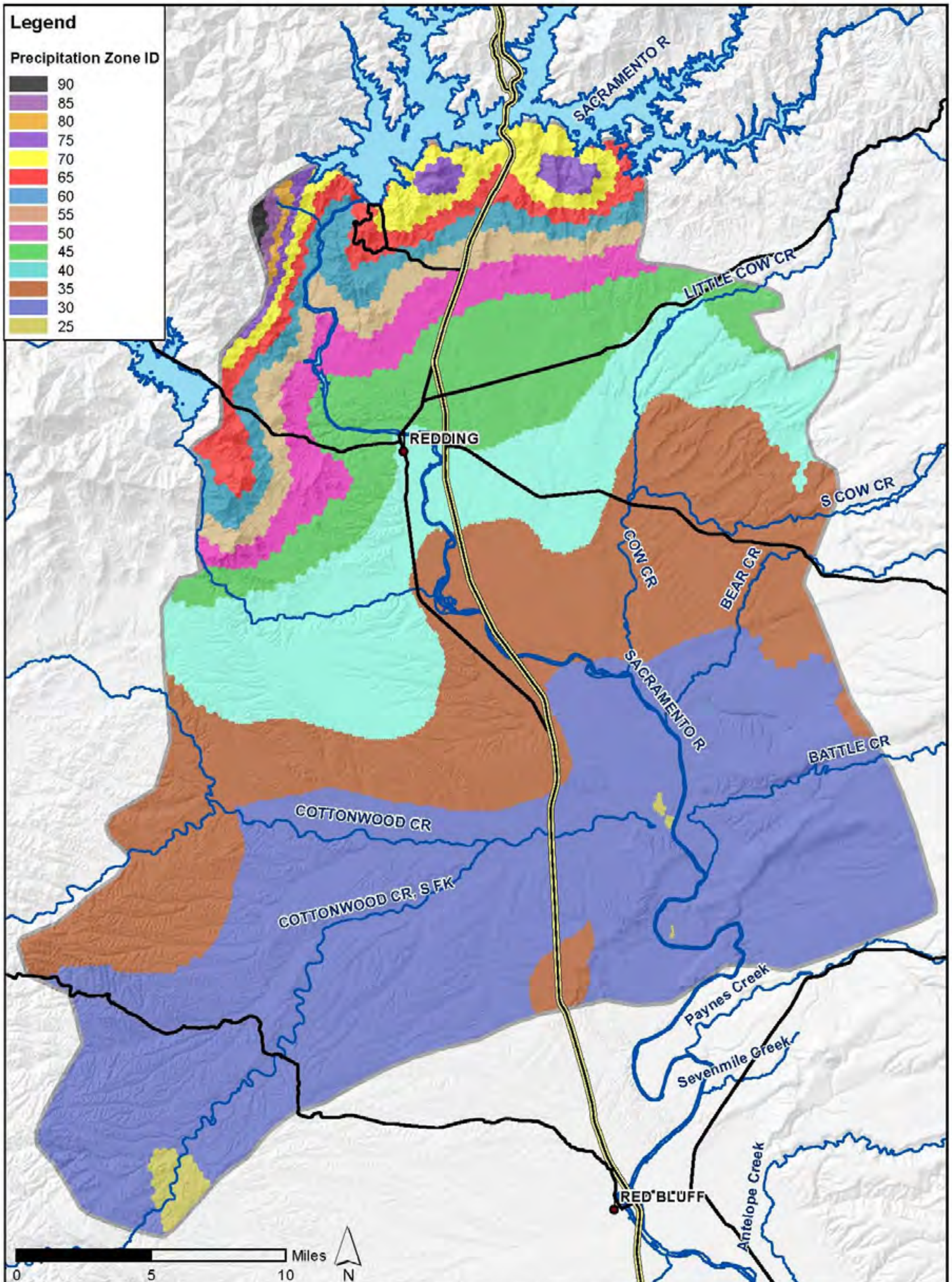
HSG data were used to estimate soil parameters used in IDC including field capacity, effective porosity, and the fraction of excess soil moisture (above field capacity) that deep percolates. HSG A soils have the lowest field capacity and the highest fraction of excess soil moisture that deep percolates while D soils have the highest field capacity and lowest fraction of excess soil moisture that deep percolates.

Precipitation Data

Time-series of monthly precipitation were developed for the entire model domain using Parameter-elevation Regression on Independent Slopes Model (PRISM) data from Oregon State University's PRISM Climate Group. These data were available at 800-meter grid spacing making it possible to provide individual time-series of precipitation to each model node. However, review of temporal and spatial variability of precipitation data indicated it was possible to aggregate areas of the model domain into precipitation regions and use a limited number of precipitation time-series. Precipitation zones were developed based on the average annual precipitation depth over the simulation period. Zones ranged from average annual precipitation of 25 inches to 90 inches in 5 inch intervals. Figure 2 illustrates the precipitation zones used in IDC.

Monthly precipitation time-series were used to calculate monthly time-series of infiltration to the root zone for use in IDC. Previous use of IDC indicated it overestimates infiltration of precipitation when performing simulations at a monthly time-step. Time-series of infiltration in the Redding Basin were developed from a previous simulation of daily precipitation, runoff, and infiltration in IDC. Daily calculated volumes were aggregated to monthly volumes to estimate the fraction of precipitation infiltrating the soil. These fractions were applied to monthly PRISM precipitation time-series for the fourteen precipitation zones and used directly in IDC.

Figure 2: Model Precipitation Zones



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IDC

IDC is a root zone soil moisture accounting model that can be used to calculate time-series of applied water demands, deep percolation past the root zone, agricultural return flows, and runoff of precipitation. IDC was used to calculate time-series of deep percolation and applied water demand for agricultural areas and deep percolation for native vegetation areas. Agricultural applied water demands were compared with observed District diversions records and in some instances adjusted by modifying irrigation efficiencies used in IDC. Table 2 is a summary of IDC input data and the source of the data.

Table 2: Summary of IDC Inputs and Source

IDC Input Data	Source
Land use	DWR Field Surveys
Soil parameters	Estimated based on NRCS HSG
Precipitation/Infiltration	PRISM/IDC simulation at daily time-step
Evapotranspiration	DWR Consumptive Use Model
Minimum soil moisture requirement	DWR Consumptive Use Model
Irrigation efficiency	DWR and calibration parameter

IDC performs calculations at a sub-region level. Inputs for soil, precipitation, evapotranspiration, minimum soil moisture, and irrigation efficiency are specified for individual sub-regions. The IDC application for the Redding Basin used a total of 141 sub-regions to define unique combinations of HSG, precipitation zone, and agricultural water districts. Irrigation parameters for most agricultural water districts and agricultural lands outside of water district boundaries were constant with the exception of Anderson-Cottonwood Irrigation District (ACID) where irrigation efficiencies were lowered to match observed water demands.

IDC was run for one acre of each crop type and native vegetation area within each sub-region and unit factors time-series were output for use in final calculation for the land use associated with each groundwater model node.

CALCULATIONS

Groundwater Pumping

A total of approximately 7,000 acres of agricultural lands are supplied by groundwater in the Redding Basin, based on the DWR survey data. Unit factors for crop applied water demand were multiplied by land use for these areas supplied from groundwater. Time-series of applied water demand for these areas are one contribution to total calculated groundwater pumping and are approximately 25,000 acre-feet on an average annual basis.

Additional agricultural pumping is estimated for lands outside of water district boundaries that may rely on a combination of available surface water and groundwater pumping. Additional groundwater pumping was assumed to meet a fraction of the applied water demand based on an approximation of available surface water in local streams. Available surface water in local streams was estimated based on Sacramento Valley Water Year Type (40-30-30 Index).

Table 3 provides the monthly fraction of applied water demand assumed to be met from groundwater pumping in these non-district lands. Months not shown are zero.

Table 3: Percent of Applied Water Demand Met by Groundwater Pumping in Non-District Lands

40-30-30 Index	May	June	July	August	September	October
Wet	0	0	0	0	0	0
Above Normal	0	0	0	0	0	0
Below Normal	0	10	40	40	40	40
Dry	20	50	50	50	50	50
Critical	30	70	70	70	70	70

Additional groundwater pumping in non-district lands is approximately 8,000 acre-feet on an average annual basis, but as much as 22,000 acre-feet in critical years. Maximum fractions in Table 3 are 70 percent of applied water demand under the assumption that some non-district lands would not be irrigated in years when surface water is not available.

Applied water demands for water districts with known surface water contracts were calculated and compared with annual contract quantities. ACID has the largest agricultural water demand and largest annual contract in the Redding Basin. ACID's CVP contract is reduced from full contract supply of 128,000 acre-feet per year in certain years of below average inflow to Lake Shasta. In these years, the CVP contract is reduced to 75 percent of full contract supply or 96,000 acre-feet. Average annual ACID diversions over the past seven years have been approximately 105,000 acre-feet. Therefore, in years of reduced CVP contract supply unmet agricultural demand within ACID is approximately 10,000 acre-feet. It was assumed that this deficit would be met through changes in district operations without additional groundwater pumping.

Comparisons of annual agricultural water diversions with CVP contract quantities for agricultural service contractors such as Bella Vista Water District and Clear Creek Community Services District (CSD) indicate diversions are typically well below contract quantities and additional groundwater pumping due to less than full contract allocation would likely be minimal.

Deep Percolation

Unit factors for deep percolation for both agricultural and native vegetation areas were multiplied by land use areas for each groundwater model node. The result of this calculation was a time-series for each model node of total deep percolation. Total deep percolation was split between precipitation and applied water based on the ratio of precipitation to applied water for a given month. For example, if total water available to an area is 10 inches in April with 6 inches from precipitation and 4 inches from applied water, then it is assumed the 60 percent of any deep percolation that occurs in April is from precipitation and the remaining 40 percent is from applied water. All deep percolation from native vegetation lands is from precipitation.

SUMMARY OF WATER BUDGET INPUTS

The following three tables present monthly summaries of water budget inputs; deep percolation and agricultural groundwater pumping, for the entire model domain. These tables illustrate the temporal variation in water budget inputs due to differences in precipitation, irrigation season, and hydrology.

Table 4: Monthly Deep Percolation of Agricultural Applied Water (acre-feet)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1980	0	0	0	2,614	4,932	3,422	7,384	7,329	3,499	348	410	0	29,939
1981	0	0	0	1,814	2,995	5,144	7,462	7,391	1,919	0	0	0	26,725
1982	0	0	0	656	6,942	1,964	6,289	7,201	2,197	0	0	0	25,250
1983	0	0	0	21	4,884	4,070	7,328	6,285	1,244	332	0	0	24,163
1984	0	0	0	2,906	6,556	4,019	7,443	6,132	3,682	0	0	0	30,739
1985	0	0	0	4,995	6,106	4,560	7,265	7,151	390	16	0	0	30,483
1986	0	0	0	2,884	4,465	5,131	7,548	7,391	643	668	766	0	29,496
1987	0	0	0	4,621	7,116	5,125	7,224	7,379	4,209	814	0	0	36,489
1988	0	0	525	4,008	1,898	2,967	7,290	7,345	4,208	1,121	0	0	29,363
1989	0	0	0	1,253	5,415	4,449	7,557	7,189	0	0	18	0	25,881
1990	0	0	0	5,887	366	4,861	6,997	6,201	3,257	550	392	0	28,509
1991	0	0	0	3,005	5,175	4,899	7,398	7,319	4,194	164	60	0	32,214
1992	0	0	0	2,128	7,000	2,841	7,270	7,358	4,180	0	0	0	30,777
1993	0	0	0	287	186	3,034	7,399	6,032	4,183	0	0	0	21,123
1994	0	0	0	3,209	3,908	5,032	7,570	7,391	4,054	1,103	0	0	32,268
1995	0	0	0	252	3,893	2,544	7,224	7,391	4,216	1,216	1,042	0	27,778
1996	0	0	0	1,557	681	5,029	7,325	7,391	3,132	103	0	0	25,218
1997	0	0	1	3,967	6,389	2,790	7,237	6,359	2,115	0	0	0	28,858
1998	0	0	0	682	119	2,654	7,421	7,391	4,083	0	0	0	22,350
1999	0	0	0	2,463	6,797	4,138	7,545	7,140	4,218	413	0	0	32,714
2000	0	0	0	786	4,766	3,985	6,925	7,283	540	0	0	0	24,285
2001	0	0	0	1,962	6,985	4,146	7,485	7,391	3,280	391	0	0	31,642
2002	0	0	0	3,908	5,473	5,134	7,546	7,358	4,189	1,236	0	0	34,844
2003	0	0	0	1	4,321	5,194	7,600	6,238	4,210	1,237	0	0	28,802
2004	0	0	1	4,352	5,922	5,079	7,497	7,353	3,964	0	0	0	34,167
2005	0	0	0	1,185	109	3,908	7,488	7,391	4,079	776	0	0	24,935
2006	0	0	0	0	5,271	4,731	7,520	7,325	4,216	1,066	0	0	30,128
2007	0	0	1	4,180	5,691	5,038	5,003	7,355	3,387	0	3	0	30,659
2008	0	0	45	6,808	6,655	5,156	7,589	7,329	4,222	148	0	0	37,953
Avg	0	0	20	2,496	4,518	4,174	7,270	7,096	3,162	403	93	0	29,233

Table 4 illustrates deep percolation of applied water occurs only during the irrigation season. Comparisons of annual deep percolation and annual applied water demand show approximately 25 percent of applied water is estimated to deep percolate. This fraction varies by water district as a function of irrigation efficiency. Irrigation efficiencies vary due to differences in operations and soil parameters.

Table 5: Monthly Deep Percolation of Precipitation (acre-feet)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1980	70,945	177,112	32,724	3,677	668	370	0	0	182	75	140	30,531	316,423
1981	144,465	65,240	90,726	606	998	0	2	0	413	8,645	145,904	151,332	608,331
1982	92,394	65,549	113,769	28,791	3	444	286	9	449	10,395	109,406	122,031	543,526
1983	166,321	204,041	301,981	33,971	595	267	6	368	448	1,943	160,797	257,196	1,127,934
1984	500	55,319	21,637	716	154	259	0	398	73	92	150,828	43,092	273,069
1985	7,271	12,061	41,515	34	376	99	11	12	172	2,949	23,773	36,576	124,850
1986	139,391	214,503	90,566	570	858	0	0	0	716	1,460	845	10,567	459,474
1987	75,369	72,457	104,151	11	25	0	41	0	0	38	1,359	88,744	342,195
1988	143,007	188	267	4,159	3,669	393	1	1	0	1	59,956	63,106	274,749
1989	36,400	2,315	199,847	693	551	169	0	12	90	17,240	7,270	0	264,587
1990	73,425	24,072	13,679	251	17,389	31	131	382	210	81	404	154	130,208
1991	1,327	13,963	206,820	602	623	15	3	0	0	48	131	10,939	234,471
1992	22,369	167,347	67,995	5,589	9	481	1	0	0	704	5,057	83,511	353,063
1993	202,902	135,194	68,871	1,216	2,655	621	0	384	0	526	7,346	78,319	498,035
1994	72,253	110,809	911	3,827	1,078	7	0	0	6	0	10,270	73,816	272,977
1995	435,138	12,942	242,500	27,032	1,416	1,779	36	0	0	0	25	131,456	852,324
1996	162,492	157,744	25,076	5,206	14,538	4	8	0	271	70	54,019	276,787	696,214
1997	182,662	869	3,701	736	339	409	1	347	316	298	83,633	59,443	332,754
1998	290,873	346,102	108,295	10,369	88,339	579	1	0	7	0	145,075	52,191	1,041,831
1999	67,414	146,692	48,376	743	31	264	0	12	0	71	16,923	4,802	285,328
2000	139,260	236,071	44,465	7,380	723	262	150	0	209	6,491	6,055	18,866	459,933
2001	109,202	114,209	32,477	618	4	249	0	0	232	194	62,237	191,821	511,244
2002	75,954	34,027	27,608	580	616	0	0	0	0	0	1,589	198,208	338,582
2003	125,922	31,818	69,121	70,976	795	0	0	363	1	0	15,065	178,031	492,092
2004	71,128	190,392	12,151	932	494	5	0	0	9	3,400	7,131	138,895	424,538
2005	92,795	50,781	68,448	3,125	20,137	422	0	0	1	58	37,862	246,851	520,482
2006	131,779	69,632	147,313	68,150	515	52	0	0	0	2	4,652	65,187	487,282
2007	2,302	120,597	0	982	588	1	757	1	212	2,262	427	46,161	174,289
2008	191,410	56,066	0	239	261	0	0	0	0	444	4,367	15,161	267,948
Avg	114,713	99,590	75,345	9,717	5,464	248	49	79	139	1,982	38,709	92,199	438,232

Table 5 illustrates deep percolation of precipitation occurs primarily outside the irrigation season and can vary significantly on an annual basis with differences in precipitation. Deep percolation during wet years such as 1983 and 1998 can be approximately an order of magnitude greater than during dry years such as 1990 and 2007. Annual deep percolation of precipitation presented in Table 5 averages approximately 24 percent of annual precipitation.

Table 6: Monthly Agricultural Groundwater Pumping (acre-feet)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1980	0	0	0	2,217	4,052	3,900	5,952	5,236	3,073	829	422	0	25,681
1981	0	0	0	1,730	4,214	8,366	10,206	9,158	4,114	0	0	0	37,788
1982	0	0	0	729	4,909	3,202	5,480	5,126	2,411	0	0	0	21,857
1983	0	0	0	76	3,935	4,253	5,862	4,706	1,880	736	0	0	21,449
1984	0	0	0	2,583	4,765	4,235	6,001	4,631	3,189	34	0	0	25,437
1985	0	0	0	3,443	5,955	7,745	10,037	8,876	2,248	470	0	0	38,775
1986	0	0	0	2,198	3,824	4,883	6,007	5,253	1,178	1,047	641	0	25,031
1987	0	0	0	3,106	6,389	8,396	9,968	9,153	6,173	2,144	0	0	45,329
1988	0	0	1,001	3,340	3,689	7,525	11,860	10,612	7,245	3,059	0	0	48,330
1989	0	0	0	1,224	5,515	7,634	10,348	8,883	282	0	117	0	34,004
1990	0	0	39	4,245	1,523	9,494	11,430	9,572	6,226	1,983	457	0	44,969
1991	0	1	0	2,235	5,975	9,361	11,785	10,683	7,233	1,405	154	0	48,834
1992	0	0	0	1,805	7,033	7,087	11,898	10,708	7,203	0	84	0	45,818
1993	0	0	0	884	1,554	3,750	6,012	4,635	3,501	220	0	0	20,556
1994	0	0	80	2,885	4,947	9,593	12,070	10,721	6,987	3,026	0	0	50,310
1995	0	0	0	406	3,378	3,377	5,932	5,253	3,516	1,581	754	0	24,196
1996	0	0	0	1,606	1,632	4,796	5,842	5,253	2,931	464	0	0	22,523
1997	0	0	234	3,522	4,747	3,581	5,932	4,746	2,551	206	0	0	25,519
1998	0	0	0	843	123	3,342	5,967	5,253	3,396	260	0	0	19,183
1999	0	0	0	2,121	4,881	4,272	6,020	5,081	3,516	880	0	0	26,771
2000	0	0	0	994	3,914	4,228	5,702	5,222	1,693	0	0	0	21,753
2001	0	0	0	1,993	6,475	7,404	10,321	9,158	5,290	1,352	0	0	41,993
2002	0	0	0	2,944	5,450	8,395	10,281	9,147	6,153	2,794	0	0	45,165
2003	0	0	0	8	3,505	4,901	5,982	4,700	3,462	1,589	0	0	24,147
2004	0	0	27	3,333	4,484	5,501	9,440	8,365	5,325	0	0	0	36,476
2005	0	0	0	1,253	873	4,286	6,020	5,253	3,424	1,177	0	0	22,285
2006	0	0	0	0	3,979	4,605	6,002	5,236	3,516	1,377	0	0	24,716
2007	0	0	293	3,267	5,530	8,270	8,062	9,144	5,388	0	245	0	40,200
2008	0	0	348	4,581	6,846	9,808	12,079	10,691	7,250	972	0	0	52,575
Avg	0	0	70	2,054	4,279	6,075	8,224	7,257	4,150	952	99	0	33,161

Table 6 shows annual agricultural groundwater pumping ranges between approximately 19,000 and 52,000 acre-feet. Pumping primarily occurs May through September with smaller quantities in March-April and October-November of some years.

COMPARISON WITH OBSERVED AND ESTIMATED VALUES

Several comparisons were made between observed or estimated values from other sources with calculated water budget inputs for select areas within the model domain. These comparisons were used to check the reasonableness of water budget inputs, not necessarily as targets for calibration.

Comparisons of applied water demands were similar to observed surface water diversions for ACID, Clear Creek CSD, and Bella Vista Water District. Calculated deep percolation of precipitation in native vegetation areas was compared to estimates of deep percolation based on relationships developed by Turner for native vegetation watersheds in California (Turner, 1985). This comparison showed calculated deep percolation in native vegetation areas was less than Turner estimates for drier precipitation zones, similar for moderate precipitation zones, and higher than Turner estimates for wetter precipitation zones. Across the entire model domain, calculated deep percolation in native vegetation areas was less than Turner estimates in dry years and more in wet years.

Comparisons of calculated applied water demand and deep percolation of applied water were made with water budgets developed by DWR Northern District for years 2002 through 2005. These comparisons were made by Detailed Analysis Unit (DAU) and county. DWR water budget data are for entire DAU-county areas while the model domain covers only a portion of DAU-county areas. However, the model domain covered the majority of DAU-county areas with significant agricultural lands in the Redding Basin. Applied water demands were similar for most DAU-county combinations. Calculated groundwater pumping exceeded DWR estimates due primarily to differences in agricultural acreage supplied from groundwater. DWR estimates were based on approximately 4,200 acres supplied from groundwater, compared to 7,000 acres based on the GIS data. Comparisons between calculated deep percolation of applied water and DWR estimates were similar for areas supplied by groundwater, but calculated values exceeded DWR estimates for areas supplied by surface water. A large disparity exists in DWR's estimate of the fraction of applied water that deep percolates between surface and groundwater sources. DWR estimates for groundwater sources were on the order of 15 to 30 percent of applied water, compared to 2 to 4 percent for surface water sources.

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Appendix E
Redding Groundwater Basin Finite-Element Model Application

Appendix E

Application of REDFEM to the Anderson-Cottonwood Irrigation District Groundwater Production Element Project

August 2011

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2525 Airpark Drive
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Contents

Acronyms and Abbreviations

ac-ft/yr	acre-feet per year
ACID	Anderson-Cottonwood Irrigation District
ACID-PW01	ACID Production Well No. 1
ACID-PW02	ACID Production Well No. 2
bgs	below ground surface
District	Anderson-Cottonwood Irrigation District
DWR	California Department of Water Resources
mg/L	milligrams per liter
REDFEM	Redding Groundwater Basin Finite-Element Model
TDS	total dissolved solids
USGS	U.S. Geological Survey

APPENDIX E

Application of REDFEM to the Anderson-Cottonwood Irrigation District Groundwater Production Element Project

1.0 Introduction

The Redding Groundwater Basin Finite-Element Model (REDFEM) was developed to forecast hydrologic system behavior resulting from implementation of proposed actions. The proposed action evaluated as part of this effort is implementation of the Anderson-Cottonwood Irrigation District (ACID or District) Proposition 50 proposed project. Appendix D to the main text (CH2M HILL, 2011) provides a complete description of the development and calibration of REDFEM. The following information describes modifications made to REDFEM to facilitate conducting the predictive simulations necessary to forecast potential impacts of the proposed project.

2.0 Model Modifications

The hydrology period used to construct and calibrate REDFEM includes January 1999 through December 2008, a period for which groundwater usage data from local districts and municipalities were most plentiful. When conducting predictive simulations, a future hydrology period must be developed. One method for developing a future hydrology period for predictive simulations is to repeat the hydrology period from the calibration simulation in the predictive simulations. The January 1999 through December 2008 hydrology period was not used with the predictive simulations because that period does not include a multi-year drought. This observation is important because groundwater use typically increases during multi-year drought periods, as surface water resources become less available. Thus, it is during dry conditions that groundwater and surface water resources are most vulnerable to impacts associated with increased groundwater use. Therefore, it is preferred to include at least one multi-year drought in the predictive simulation hydrology when forecasting impacts on groundwater resources from proposed project implementation.

The 1976 through 1977 period was critically dry in the Sacramento Valley, which includes the Redding Groundwater Basin (California Department of Water Resources [DWR], 2011). Unfortunately, municipal and water district records for the 1976 through 1977 period, and other critically dry periods before 1999, are not available for the Redding Groundwater Basin. Therefore, model input data representing a multi-year drought was synthesized to facilitate forecasting impacts of the proposed project over a variety of hydrologic conditions, including a multi-year drought.

A 14-year predictive simulation period was developed using the 1999 through 2008 data used to calibrate REDFEM, combined with 4 years of hydrology data to mimic a severe drought condition (similar to water years 1974 through 1977). Water years 1974 and 1975 were wet years in the Sacramento Valley. To replicate this 2-year period, boundary conditions reflecting 2006 (a wet year for which groundwater use data are available in the Redding Groundwater Basin) were simulated for 2 consecutive years. To replicate the 1976 critically dry water year, water budget components from 2008, another critically dry year, were used. However, the following 1977 critically dry year had even less rainfall than 1976. So, to create hydrologic inputs more closely analogous to 1977, monthly estimates of groundwater recharge for water year 1991, the lowest rainfall year for which spatially detailed precipitation data were available for the REDFEM domain (PRISM Climate Group, 2010), were modified. Precipitation during water year 1977 was 26 percent less than in 1991, according to precipitation data collected at Shasta Dam (National Climatic Data Center, 2011). Therefore, to generate a hydrology closely approximating 1977, the calculated 1991 groundwater recharge from precipitation was reduced by 26 percent (multiplied by 0.74).

Table E-1 lists the simulated years of agricultural and urban water balance components, groundwater recharge from precipitation, and hydrologic classifications of each simulated year.

TABLE E-1
Basis for Hydrology Conditions Used for the Predictive Simulations
Application of REDFEM to the ACID Groundwater Production Element Project

Predictive Simulation Year	Analogous Historical Water Year	Water-year Hydrologic Classification for the Sacramento Valley	Water-year Basis for Agricultural and Urban Water Balance	Water-year Basis for Groundwater Recharge from Precipitation
1	1999	Wet	1999	1999
2	2000	Above normal	2000	2000
3	2001	Dry	2001	2001
4	2002	Dry	2002	2002
5	2003	Above normal	2003	2003
6	2004	Below normal	2004	2004
7	2005	Above normal	2005	2005
8	2006	Wet	2006	2006
9	2007	Dry	2007	2007
10	2008	Critical	2008	2008
11	1974	Wet	2006	2006
12	1975	Wet	2006	2006
13	1976	Critical	2008	2008
14	1977	Critical	2008	74% of 1991

Note:

The predictive simulation begins on January 1 of water year 1999; all other years are simulated as full water years.

3.0 Model Application

The following sections describe how the proposed project was simulated in REDFEM and how potential impacts on groundwater resources were forecast.

3.1 Description of Proposed Project

The purpose of the proposed project is to improve the flexibility and reliability of ACID's water supply, particularly during dry and critically dry water years. In 2004, ACID's surface water rights were reduced from 165,000 acre-feet per year (ac-ft/yr) to 121,000 ac-ft/yr as part of the re-negotiation of their 40-year Settlement Contract. Furthermore, control of the District's surface water delivery system is maintained at the head of the 35-mile main canal located at its diversion on the Sacramento River in the City of Redding. The limited ability to manage water levels along intermediate portions of the canal presents difficulty with the timely delivery of water to users located near downstream portions of ACID's service area. Implementation of this proposed project would help improve the reliability of water delivery to meet agricultural water needs within ACID's service area.

REDFEM was used to evaluate a proposed project involving the installation and operation of two groundwater production wells in Shasta County, California. The proposed ACID Production Well No. 1 (ACID-PW01) would be located in the City of Anderson (Township 30 North, Range 4 West, Section 23; Mount Diablo Meridian; 122˚17'19.15"W longitude, and 40˚26'19.34"N latitude [North American Datum of 1983]) (see Figures E-1 and E-2; figures are located at the end of this report).

The proposed ACID Production Well No. 2 (ACID-PW02) would be located approximately 0.5 mile northwest of the town of Cottonwood, California (Township 29 North, Range 4 West, Section 2; Mount Diablo Meridian; 122°17'30.03"W longitude, and 40°23'39.08"N latitude [North American Datum of 1983]) (see Figures E-1 and E-3).

Both wells would be nominally 500 feet deep or less, each with a target capacity of 3,500 gallons per minute and a nominal screen length of approximately 300 feet. It is assumed the production wells would operate 24 hours per day according to the following schedule:

- **Noncritical water year[1]:** ACID-PW01 would not operate during noncritical water years. ACID-PW02 would operate from June through October to augment water supply in areas where water conveyance is seasonally limited by aquatic vegetative growth in the canal (aquatic vegetation grows in the canal throughout the delivery season, thereby limiting delivery capacity).
- **Critical water year:** Both production wells would operate from April through October during critically dry years to augment water supply and improve water delivery reliability.

[1] ACID receives its full Sacramento River Settlement Contract amount in all years other than years designated as "Shasta Critical Years."

3.2 Proposed Project Simulation

The predictive version of REDFEM carried forward the assumptions incorporated into the calibrated version of REDFEM described in Appendix D to the main text (CH2M HILL, 2011), except where modifications were made, as described in Section 2.0. This subsection describes additional changes to the predictive model that were necessary to simulate the proposed project.

To simulate implementation of the proposed project, groundwater production was assigned in accordance with the operational assumptions described in Section 3.1. Groundwater pumping was assigned spatially at the REDFEM node closest to the proposed well location. The proposed groundwater pumping was apportioned equally to Model Layers 2 and 3, which are 300 feet thick, collectively. At the locations of the proposed wells, the approximate model layer interfaces are as follows:

- Model Layer 1: 65 to 115 feet below ground surface (bgs) (0 to 50 feet below the water table)
- Model Layer 2: 115 to 215 feet bgs (50 to 150 feet below the water table)
- Model Layer 3: 215 to 415 feet bgs (150 to 350 feet below the water table)
- Model Layer 4: 415 to 2,095 feet bgs (350 to 2,030 feet below the water table)

3.3 Approach for Evaluating Impact on Hydrologic System

Four categories of potential groundwater-related impacts were considered when evaluating the proposed project:

- Decrease in groundwater levels
- Decrease in groundwater discharge to streams
- Subsidence of the land surface
- Degradation of groundwater quality

Two REDFEM simulations were conducted to forecast the potential incremental impacts of implementation of the proposed project. First, a baseline simulation was conducted that did not include the operation of the proposed project. Next, a project simulation was conducted that included the operation of the proposed project as described in Sections 3.1 and 3.2. Using the results of these simulations, the "incremental drawdown" in groundwater levels due to project operations was computed by subtracting the simulated groundwater levels from the with-project simulation from groundwater levels from the baseline simulation at each REDFEM node and for each month over the 14-year predictive simulation period. To be conservative with respect to third-party impacts, the maximum impact on groundwater levels was considered to be the period with the largest forecast magnitude of incremental drawdown near the pumping well, rather than the period with the largest spatial extent (although smaller magnitude) of incremental drawdown.

Incremental streamflow depletion that may result from project implementation was computed in a similar manner, except the difference in stream gains and losses between the with-project and baseline simulations was computed. Forecasting water resource impacts in this manner provides an assessment of incremental project-related impacts on groundwater and surface water resources with consideration of dynamic hydrologic conditions (such as droughts and wet periods). Groundwater-level impacts due to project operations are discussed in Section 3.4.1.

Operation of the proposed project would reduce streamflow by increasing streambed infiltration, intercepting groundwater that would have otherwise discharged to surface water bodies, or some combination thereof. Streams with the greatest potential for impact were identified by delineating areas with forecast incremental drawdowns in the shallow aquifer of 1 foot or greater as a result of implementing the proposed project. Available historical streamflow data were obtained for streams located within these areas and compared with simulated streamflow depletions to assess the potential magnitude of streamflow impacts. Discussion of stream impacts is included in Section 3.4.2.

Land subsidence has never been monitored in the Redding Groundwater Basin, but is expected to be negligible given the lack of chronically depressed groundwater levels, and because the current magnitude of groundwater pumping in the basin represents a small fraction of the amount of water available for groundwater recharge. Nonetheless, the potential for land subsidence was qualitatively evaluated and is discussed in Section 3.4.3.

The potential for changes to groundwater quality from project implementation was qualitatively evaluated by noting potential changes to groundwater flow patterns caused by the proposed project. Discussion of impacts on groundwater quality is included in Section 3.4.4.

Incremental impacts would be considered significant if any of the following conditions occur as a direct result of implementing the proposed project:

- Groundwater levels decrease enough such that well yields of pre-existing and nearby wells decrease to a rate that would not support existing land uses or planned uses for which permits have been granted (for example, lowering groundwater levels enough that a pre-existing and nearby production well can no longer operate at historical capacity).
- Streamflows decrease enough such that its rate would not support existing stream uses or planned uses for which permits have been granted (for example, reducing groundwater discharge to a stream enough that the diversions from a stream can no longer be operated at historical diversion rates by users with appropriate surface water rights).
- Groundwater levels in an area susceptible to subsidence decrease to below historical minimums.
- Groundwater flow directions in an area of poor groundwater quality change in a way that would tend to degrade areas of good groundwater quality.

3.4 Proposed Project Results

3.4.1 Groundwater Impacts

Figures E-4 and E-5 show the forecast incremental drawdown in the shallow and regional aquifer systems that result from implementing the proposed project. The distribution in incremental drawdown shown on Figures E-4 and E-5 represent conditions comparable to the end of the 1976 through 1977 historical drought (the end of September 1977). As described in Section 3.3, these forecasts represent the incremental drawdown that occurs solely from implementation of the proposed project.

Figure E-4 shows the maximum forecast incremental drawdown in the shallow aquifer that occurs as a result of the proposed project. Shallow aquifer incremental drawdown refers to changes in groundwater levels within approximately the upper 50 feet of the unconfined aquifer. This incremental drawdown is forecast to occur at the end of the water year (September 30), prior to the rainy season. Shallow aquifer incremental drawdown resulting from implementation of the proposed project is forecast to range from approximately 0 to 14 feet, with incremental drawdown not exceeding 5 feet in most areas. A maximum incremental drawdown of 14 feet is forecast in the immediate vicinity of ACID-PW02, and is projected to dissipate to 7.1 feet within 0.25 mile and to 4 feet within 0.5 mile of the well. Shallow aquifer incremental drawdown is projected to dissipate to 4.5 feet within 0.25 mile and to 3 feet within 0.5 mile of ACID-PW01.

Regional aquifer incremental drawdown, shown on Figure E-5, refers to maximum changes in groundwater levels at the depth interval where the majority of groundwater production from the proposed wells is assigned. As noted in Section 3.2, groundwater pumping for the proposed project was assigned to Model Layers 2 and 3. Forecast incremental drawdowns for each of these model layers were evaluated to determine which layer showed the largest forecast incremental drawdown. The most incremental impact was forecast in Model Layer 2. As shown on Figure E-5, the model results indicate that maximum regional aquifer incremental drawdown resulting from project implementation ranges from 0 to 25 feet by the end of the pumping season, with incremental drawdown not exceeding 5 feet in most areas. The areal extent of the regional aquifer incremental drawdown is similar to that of the shallow aquifer. A maximum incremental drawdown of 25 feet is forecast in the immediate vicinity of ACID-PW02, and is projected to dissipate to 7.2 feet within 0.25 mile and to 4 feet within 0.5 mile of the well. Regional aquifer incremental drawdown is projected to dissipate to 4.6 feet within 0.25 mile and to 3 feet within 0.5 mile of ACID-PW01.

Pumping wells in the District are not near enough to the proposed project wells to be adversely affected. Forecast incremental drawdowns dissipate with a relatively small distance from the proposed wells, and incremental drawdowns of a few feet or less is not expected to prevent normal operation of pre-existing production wells.

3.4.2 Surface Water Impacts

Operation of the proposed project could result in reduced streamflow by increasing streambed infiltration, intercepting groundwater that would have otherwise discharged to surface water bodies, or some combination thereof.

REDFEM was not configured to forecast impacts on the ACID main canal. Main canal seepage is specified on a monthly basis (see Appendix D). As a result, canal seepage does not increase in response to declining groundwater levels in the model. This approach is conservative in terms of forecast groundwater-level impacts because it may overestimate the decline in groundwater levels from proposed pumping. Where the ACID main canal is in contact with the water table, more seepage would occur in response to declining groundwater levels, thereby reducing the amount of the groundwater-level decline. A smaller decline in groundwater levels would also result in less forecast impact on nearby streams.

For the proposed project, Anderson and Cottonwood Creeks are the only simulated streams located within the area of forecast incremental drawdown of 1 foot or greater in the shallow aquifer. Because no stream gage data are available for Anderson Creek, comparison of forecast stream impacts on measured streamflow is not possible. Measured streamflow data are available for Cottonwood Creek. Because both Anderson and Cottonwood Creeks are tributary to the Sacramento River, which is the primary stream in the Redding Groundwater Basin with available measured streamflow data, forecast stream impacts are compared with available measured streamflow data from Cottonwood Creek and the Sacramento River on Figure E-6. Streamflow reductions would represent a small percentage (less than 0.5 percent) of the total streamflow, as measured at U.S. Geological Survey (USGS) Gage No. 11377100 above Bend Bridge near the southern end of the REDFEM domain. Streamflow reductions would also represent a small percentage (approximately 2 percent or less) of the total streamflow, as measured at USGS Gage No. 11376000 near the town of Cottonwood.

3.4.3 Land Subsidence

Land subsidence is the decline in ground-surface elevation resulting from natural forces (such as earthquakes) and anthropogenic activities (for example, groundwater, oil, and gas extraction). Land subsidence can be elastic (temporary compaction of subsurface material that rebounds as groundwater levels recover) or inelastic (permanent compaction of subsurface material).

Land subsidence has never been monitored in the Redding Groundwater Basin, but is expected to be negligible given the lack of chronically depressed groundwater levels, and because the current magnitude of groundwater pumping in the basin represents a small fraction of the amount of water available for groundwater recharge. In particular, the Anderson Subbasin, where the proposed project would operate, has been characterized as having low potential for subsidence (DWR, 2003a). No areas susceptible to land subsidence have been identified in the Redding Groundwater Basin.

3.4.4 Groundwater Quality

Groundwater quality in the Redding Groundwater Basin was evaluated in a USGS report published in 1983 (Pierce, 1983). That report summarized groundwater quality data from 85 wells that were sampled in 1979. Most of these wells were completed in the Tuscan or Tehama Formations. The report concluded that groundwater quality in these formations was generally good to excellent for most uses. Samples from 84 wells were analyzed for total dissolved solids (TDS), and 66 samples had TDS concentrations below 200 milligrams per liter (mg/L). The range of TDS concentrations was 95 to 424 mg/L. Wells along the eastern portion of the Redding Groundwater Basin typically have the best water quality because of Sierra Nevada’s low-salinity runoff. Areas with poorer groundwater quality occur primarily where some wells are completed in or near the marine sediments of the Chico Formation.

DWR monitors groundwater quality in seven wells in the Anderson Subbasin, where the proposed project would operate. The overall groundwater quality of those wells is considered good (DWR, 2003a). No areas of poor groundwater quality have been identified near the proposed project. Figures E-7 and E-8 illustrate the forecast groundwater flow directions at the end of the predictive baseline and project simulations, in the shallow and regional aquifers, respectively. The end of the predictive simulation corresponds to the end of a multi-year drought, similar to that which occurred in 1976 through 1977. As illustrated on Figures E-7 and E-8, according to REDFEM, temporary changes in groundwater flow directions would be localized around the proposed project wells in both the shallow and regional aquifers. Therefore, it is not anticipated that operation of the project wells would alter the pre-existing distribution of groundwater quality in the basin.

4.0 Outcome of Impacts Evaluation

Predictive versions of REDFEM were used to forecast potential impacts on water resources from implementation of the proposed project. The REDFEM simulations are imperfect in that they do not accurately describe all aspects of interrelated physical processes beneath the proposed project area. Future groundwater levels and flow directions will not necessarily follow those indicated with the predictive versions of REDFEM; however, the details included in REDFEM have resulted in a model that is suitable for its intended application. The predictions described in this appendix are considered plausible and reasonable, given the available data and modeling objectives.

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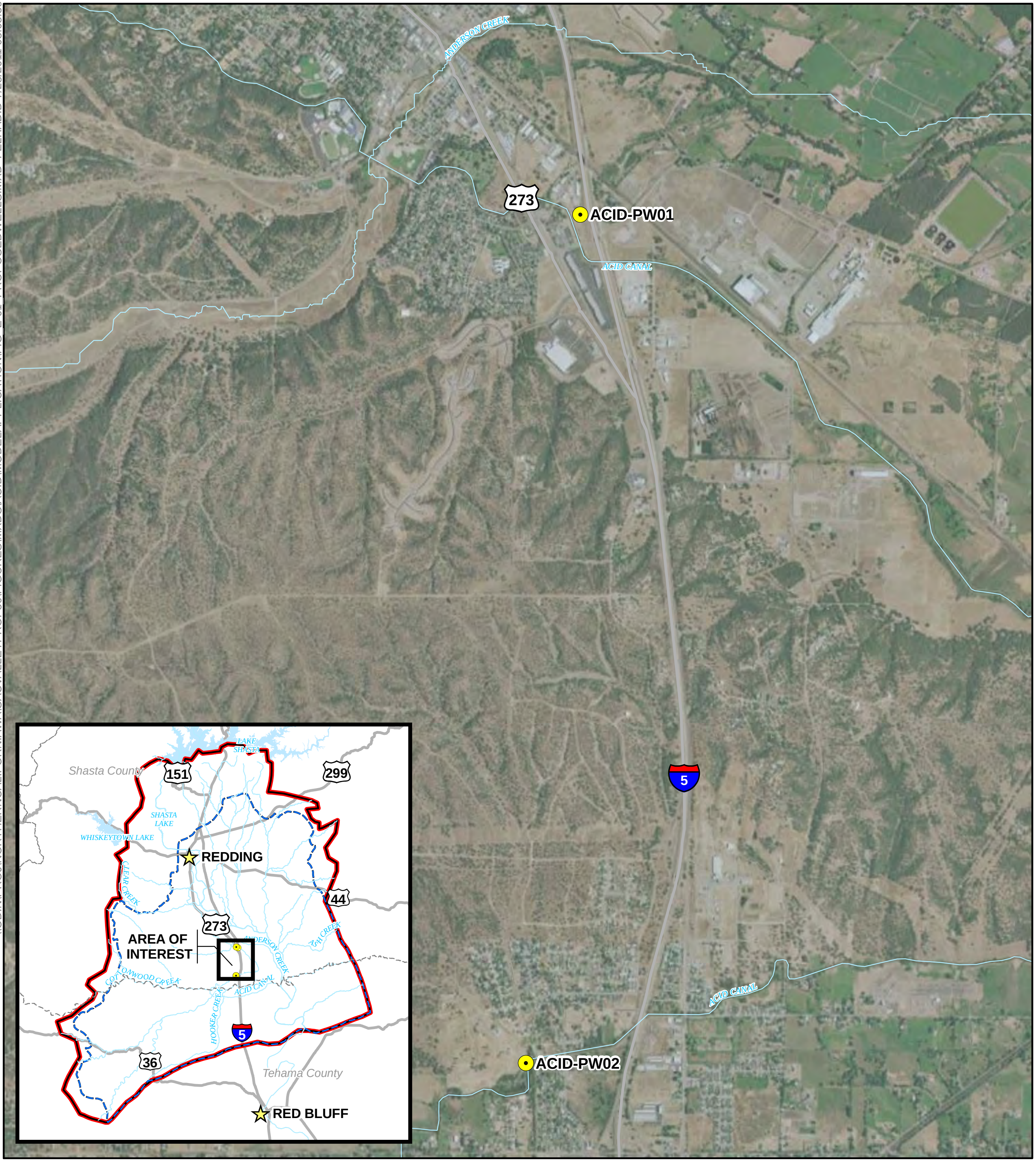
Figures



LEGEND

PROPOSED PRODUCTION WELL

REDDING GROUNDWATER BASIN BOUNDARY

STUDY AREA AND REDFEM BOUNDARY

STREAM/CANAL LOCATION

0 0.5 1 Miles

N

NOTE:

SOURCE OF AERIAL PHOTOGRAPH, ESRI, 2011.

FIGURE E-1
ACID PROPOSED WELL LOCATIONS
APPLICATION OF REDFEM TO THE ACID GROUNDWATER PRODUCTION ELEMENT PROJECT

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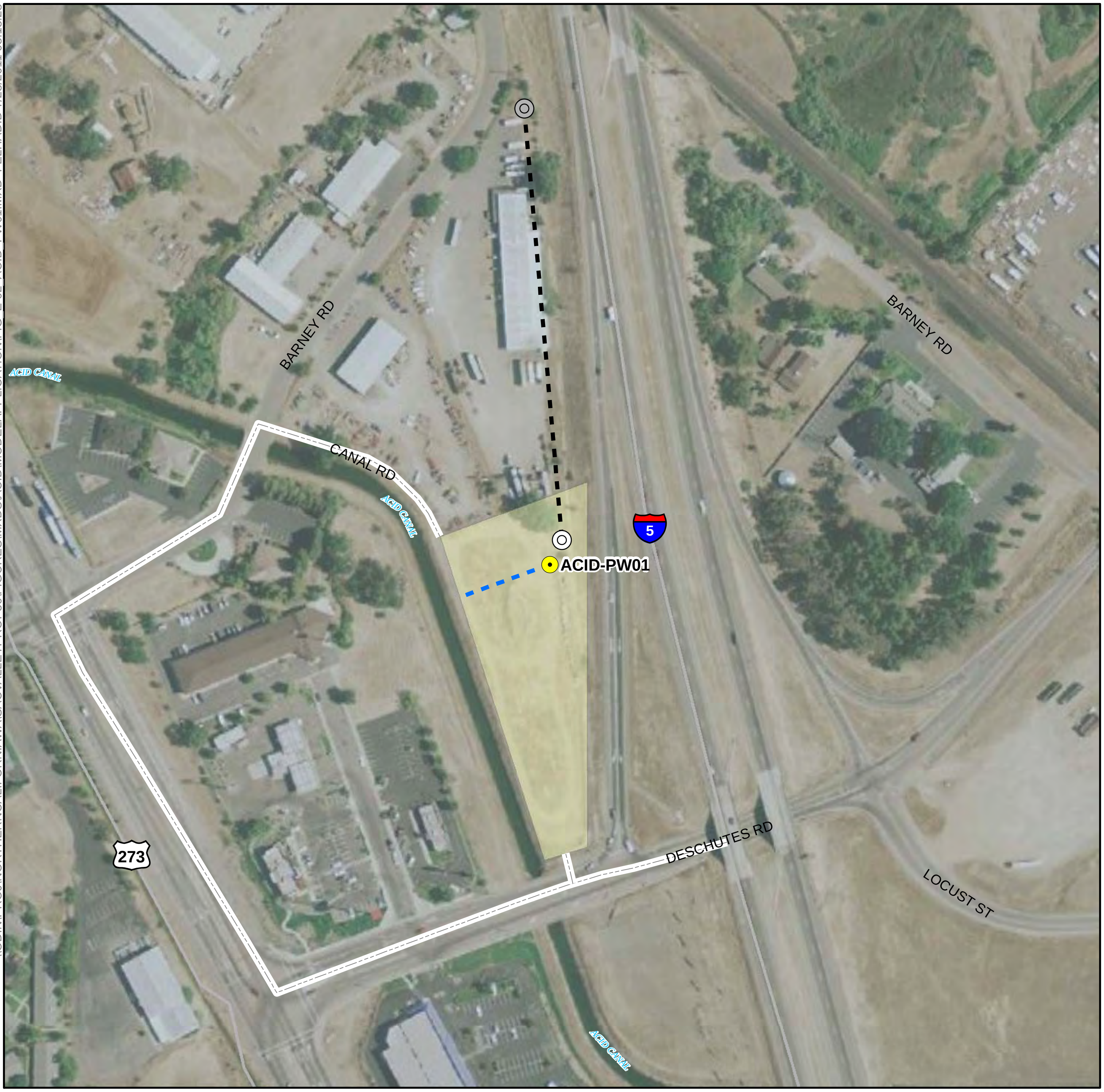

LEGEND

- PROPOSED PRODUCTION WELL
- PROPOSED POWER POLE
- EXISTING POWER POLE
- EXISTING ACCESS ROUTE
- PROPOSED CONVEYANCE LINE TO CANAL
- PROPOSED POWER POLE LINE
- PROJECT AREA

NOTE:

SOURCE OF AERIAL PHOTOGRAPH, ESRI, 2011.

N

0 250 500 Feet

FIGURE E-2
ACID-PW01 LOCATION MAP
APPLICATION OF REDFEM TO THE ACID GROUNDWATER PRODUCTION ELEMENT PROJECT

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\\ODIN\PROJ\NORTHERNCALIFORNIAWA\SACVALLEYPROP50\FIGURES\MXDS\ACID\MODELAPPLICATION\FIG_E-03_ACID_PW02.MXD FELHADID 7/28/2011 08:12:56

LEGEND

- PROPOSED PRODUCTION WELL
- EXISTING POWER POLE
- EXISTING ACCESS ROUTE
- PRIVATE ACCESS ROAD
- PROPOSED CONVEYANCE LINE TO CANAL
- PROJECT AREA

NOTE:

SOURCE OF AERIAL PHOTOGRAPH, ESRI, 2011.

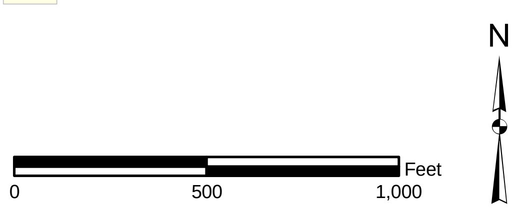

FIGURE E-3
ACID-PW02 LOCATION MAP
APPLICATION OF REDFEM TO THE ACID GROUNDWATER PRODUCTION ELEMENT PROJECT

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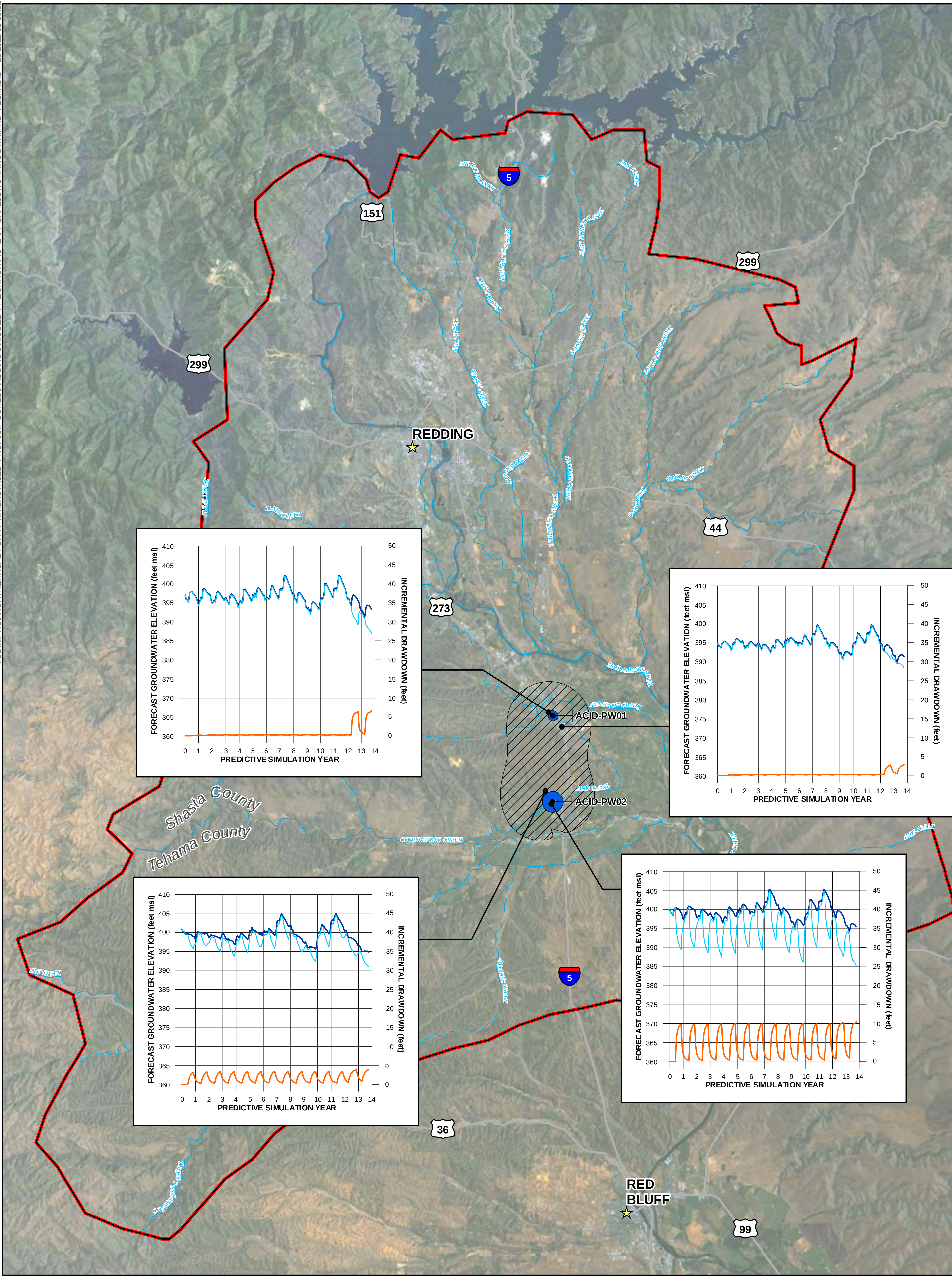

LEGEND

• LOCATION OF FORECAST GROUNDWATER ELEVATION AND INCREMENTAL DRAWDOWN

FORECAST INCREMENTAL DRAWDOWN (feet)

- 1 to 5
- 5 to 10
- 10 to 15
- 15 to 20
- 20 to 30
- STUDY AREA AND REDFEM BOUNDARY
- INCREMENTAL DRAWDOWN
- BASELINE GROUNDWATER ELEVATION
- PROJECT GROUNDWATER ELEVATION

N

0 3.5 7 Miles

NOTES:

MSL = MEAN SEA LEVEL.

SOURCE OF AERIAL PHOTOGRAPH, ESRI, 2011.

FIGURE E-4
FORECAST INCREMENTAL DRAWDOWN IN THE SHALLOW AQUIFER
APPLICATION OF REDFEM TO THE ACID GROUNDWATER PRODUCTION ELEMENT PROJECT

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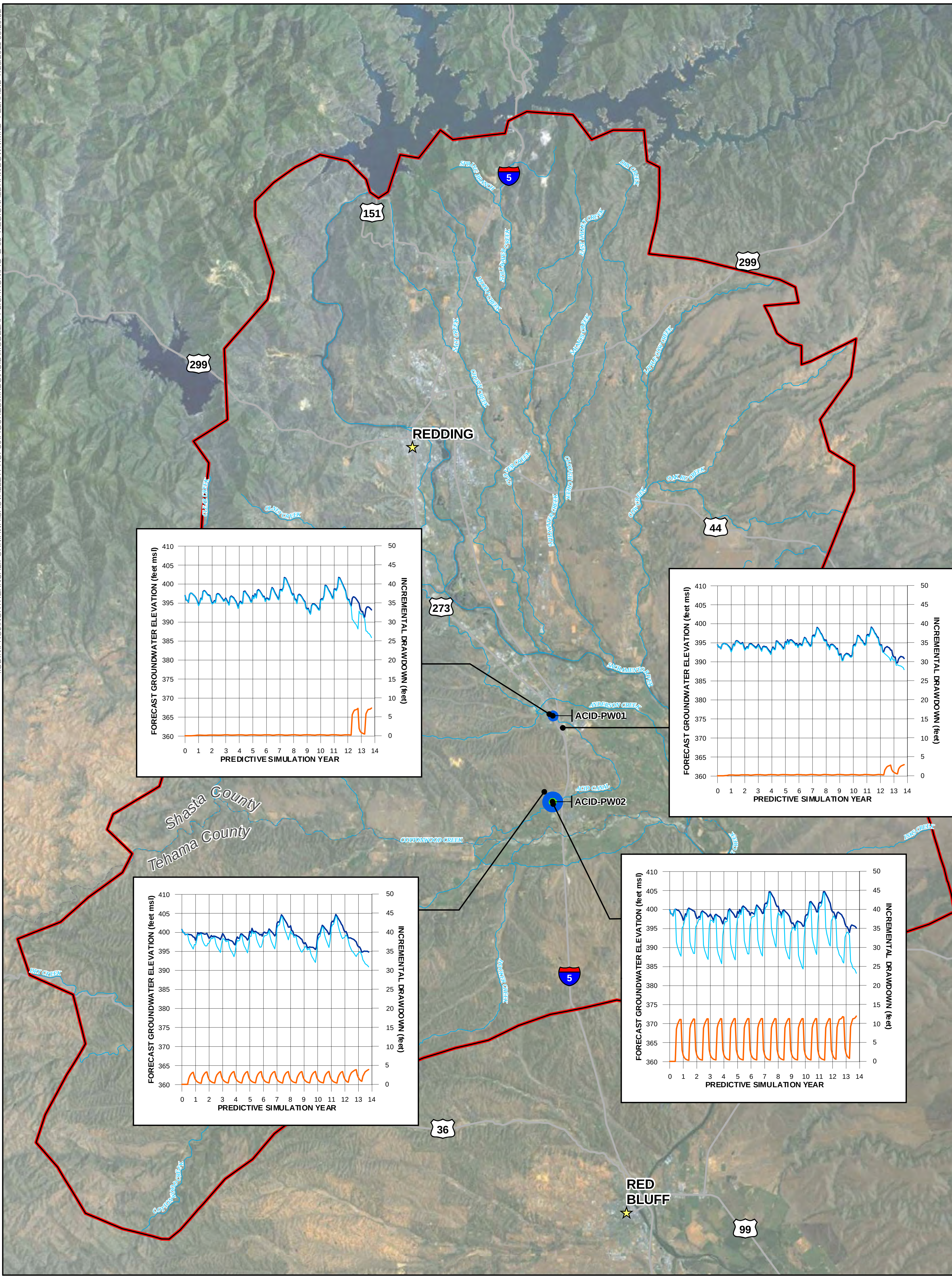

LEGEND

- LOCATION OF FORECAST GROUNDWATER ELEVATION AND INCREMENTAL DRAWDOWN

FORECAST INCREMENTAL DRAWDOWN (feet)

- 5 to 10
- 10 to 15
- 15 to 20
- 20 to 30
- STUDY AREA AND REDFEM BOUNDARY
- INCREMENTAL DRAWDOWN
- BASELINE GROUNDWATER ELEVATION
- PROJECT GROUNDWATER ELEVATION

N

0 3.5 7 Miles

NOTES:

MSL = MEAN SEA LEVEL.

SOURCE OF AERIAL PHOTOGRAPH, ESRI, 2011.

FIGURE E-5
FORECAST INCREMENTAL DRAWDOWN IN THE REGIONAL AQUIFER
APPLICATION OF REDFEM TO THE ACID GROUNDWATER PRODUCTION ELEMENT PROJECT

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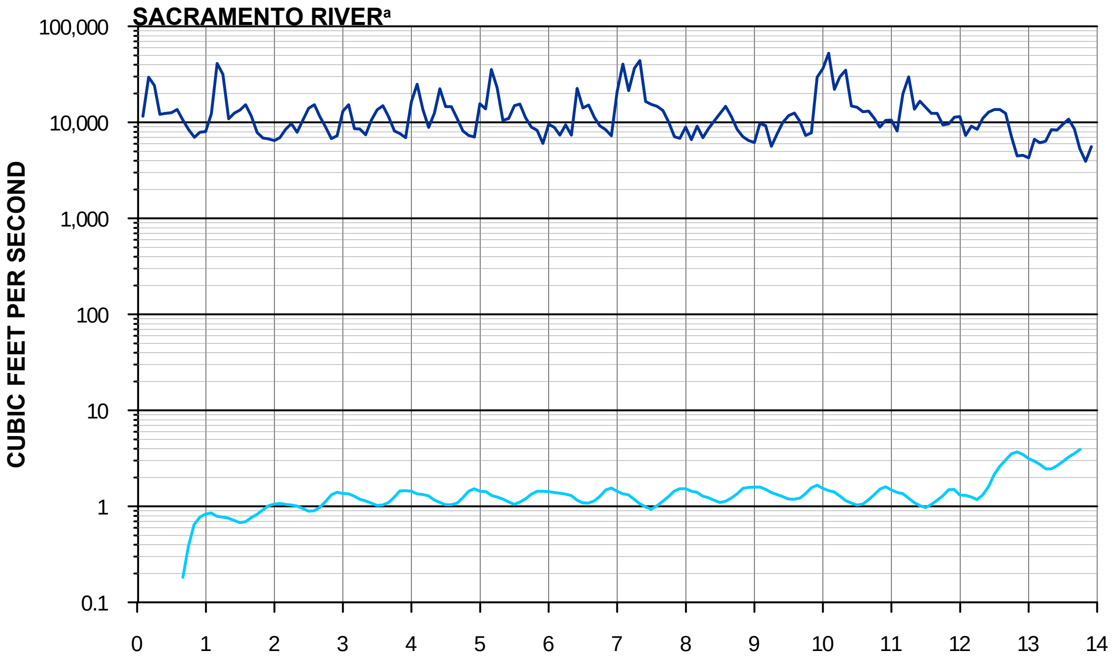

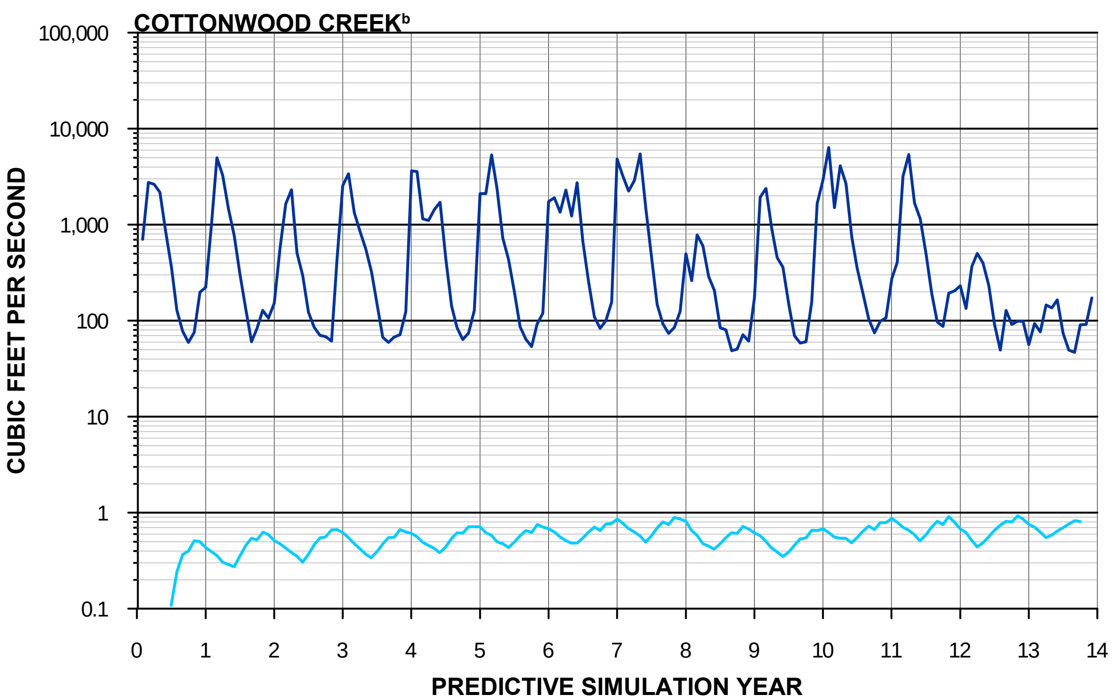

LEGEND

MEASURED STREAMFLOW

FORECAST STREAMFLOW REDUCTION

PREDICTIVE SIMULATION YEAR	WATER-YEAR HYDROLOGY
1	1999
2	2000
3	2001
4	2002
5	2003
6	2004
7	2005
8	2006
9	2007
10	2008
11	1974
12	1975
13	1976
14	1977

[a]MEASURED STREAMFLOW AT USGS GAGE 11377100, SACRAMENTO RIVER ABOVE BEND BRIDGE NEAR RED BLUFF, CALIFORNIA.

[b]MEASURED STREAMFLOW AT USGS GAGE 11376000, COTTONWOOD CREEK NEAR COTTONWOOD, CALIFORNIA.

FIGURE E-6
FORECAST STREAM IMPACTS
APPLICATION OF REDFEM TO THE ACID GROUNDWATER PRODUCTION ELEMENT PROJECT

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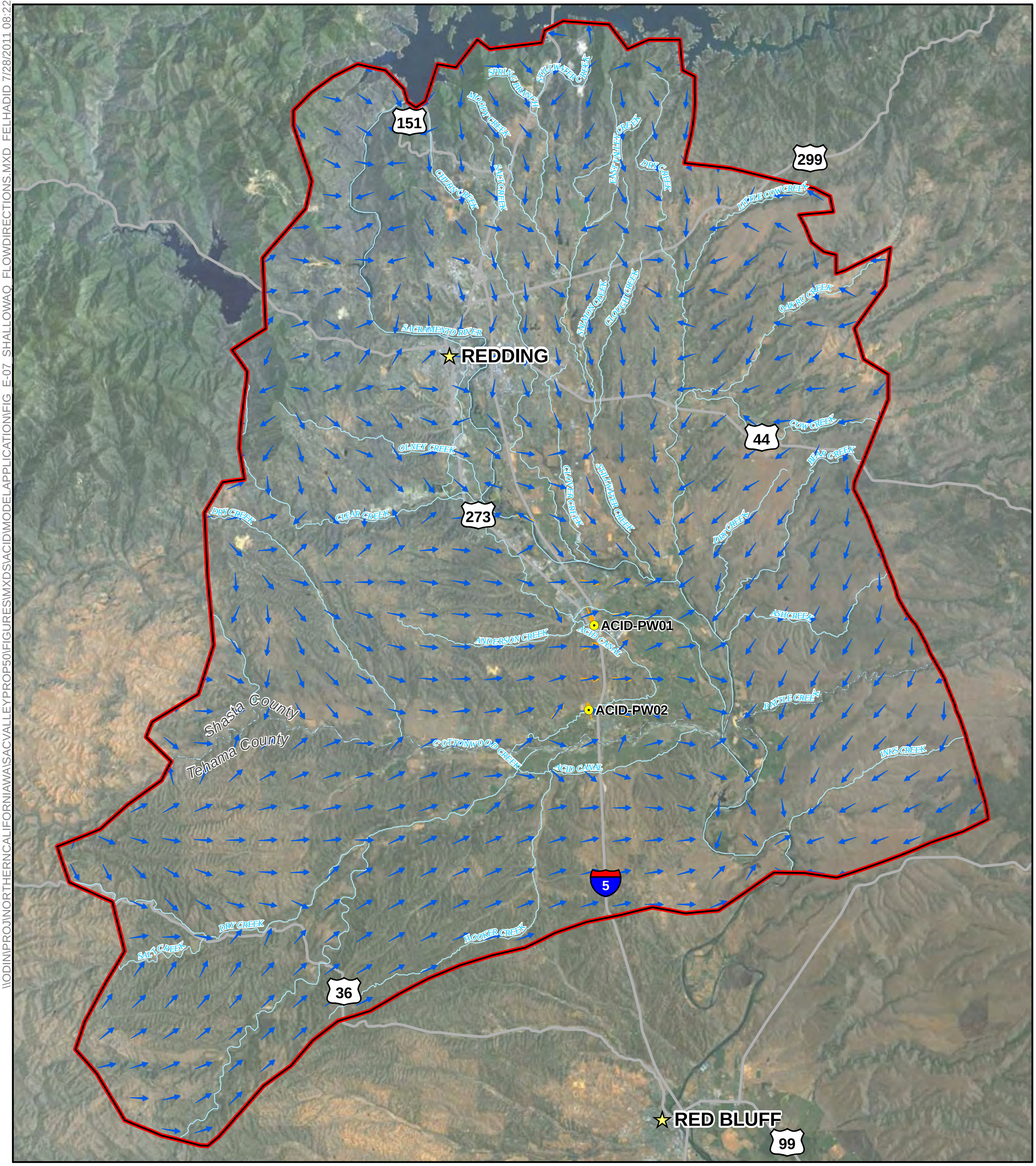

LEGEND

- PROPOSED PRODUCTION WELL
- GROUNDWATER FLOW DIRECTION – BASELINE SIMULATION
- GROUNDWATER FLOW DIRECTION – PROJECT SIMULATION
- STUDY AREA AND REDFEM BOUNDARY

0 5 10 Miles

N

NOTE:

SOURCE OF AERIAL PHOTOGRAPH, ESRI, 2011.

FIGURE E-7
FORECAST GROUNDWATER FLOW DIRECTIONS IN THE SHALLOW AQUIFER

APPLICATION OF REDFEM TO THE ACID GROUNDWATER PRODUCTION ELEMENT PROJECT

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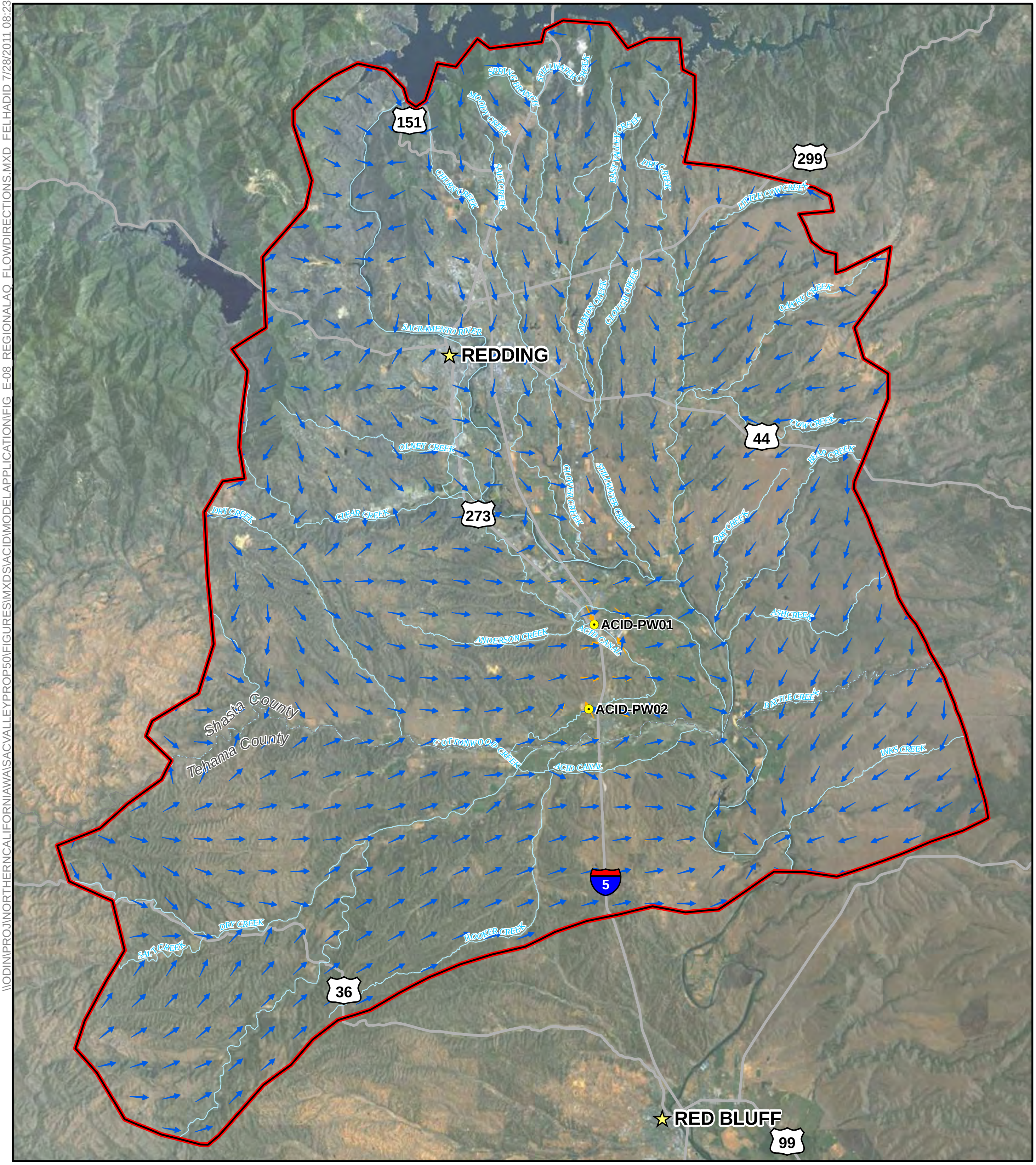

LEGEND

- PROPOSED PRODUCTION WELL
- GROUNDWATER FLOW DIRECTION – BASELINE SIMULATION
- GROUNDWATER FLOW DIRECTION – PROJECT SIMULATION
- STUDY AREA AND REDFEM BOUNDARY

0 5 10 Miles

N

NOTE:

SOURCE OF AERIAL PHOTOGRAPH, ESRI, 2011.

FIGURE E-8
FORECAST GROUNDWATER FLOW DIRECTIONS IN THE REGIONAL AQUIFER
APPLICATION OF REDFEM TO THE ACID GROUNDWATER PRODUCTION ELEMENT PROJECT

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