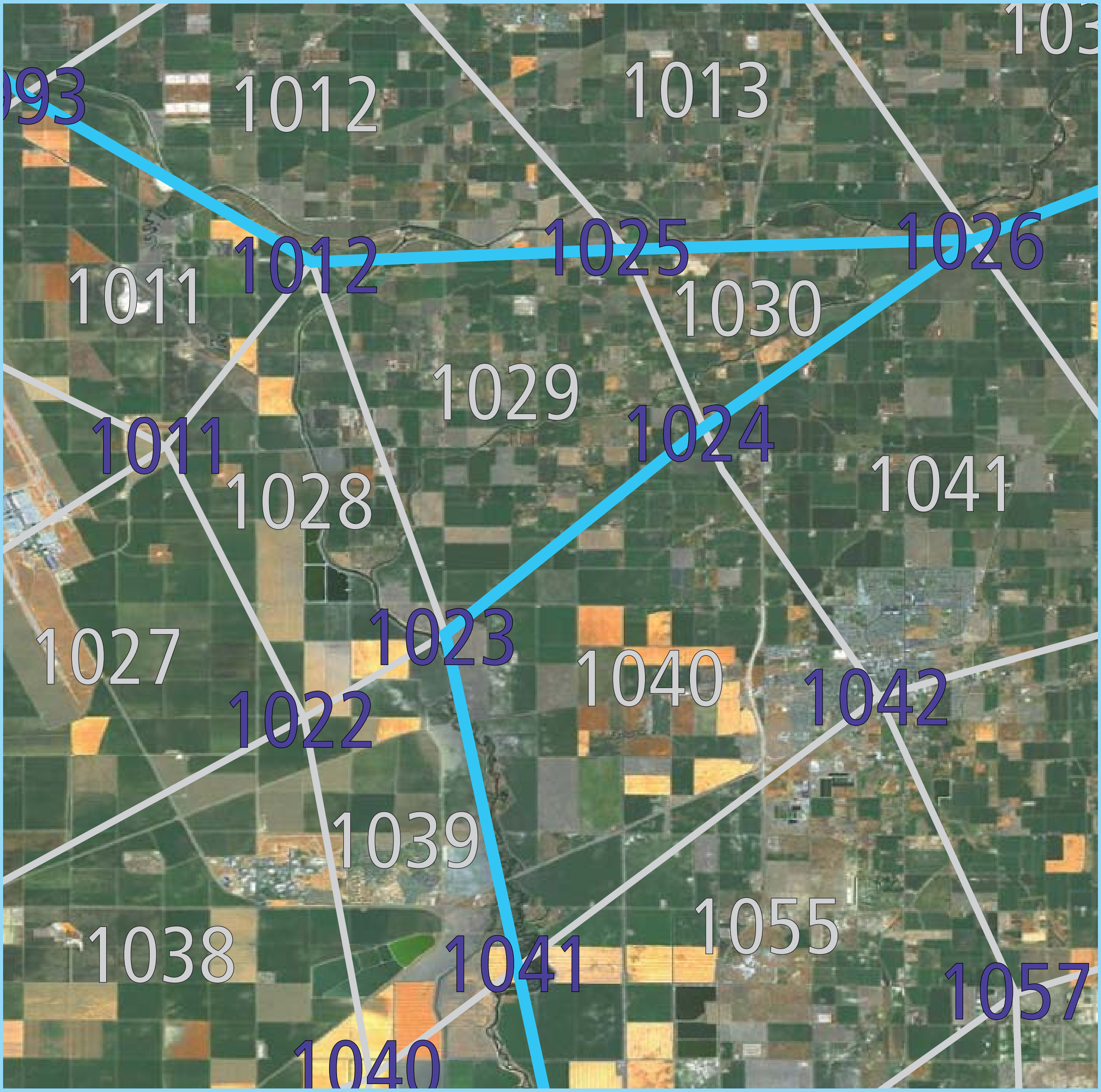
DWR Technical Memorandum

User’s Manual

for the

California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG

Charles F. Brush and Emin C. Dogrul



Bay-Delta Office, California Department of Water Resources, 1416 Ninth Street, Sacramento, CA 95814

C2VSim-CG Version R374, released June 2013 (v1.1 3/2016)

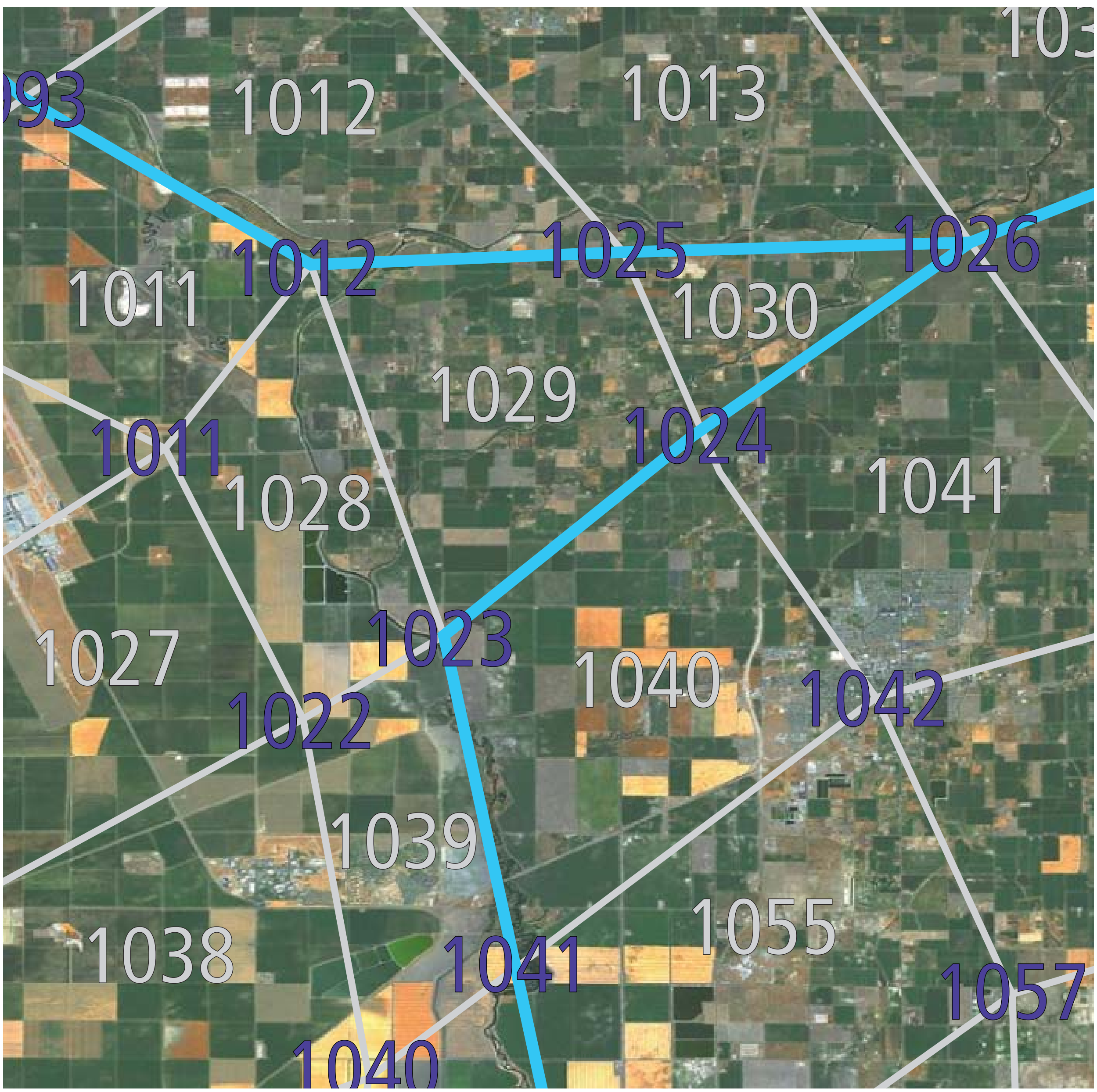
DWR Technical Memorandum

User’s Manual

for the

California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG

Charles F. Brush, Emin C. Dogrul



Bay-Delta Office, California Department of Water Resources, 1416 Ninth Street, Sacramento, CA 95814

C2VSim-CG Version R374, released June 2013 (v1.1 3/2016)

DWR Technical Memorandum: User's Manual for the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG
Authors: Charles F. Brush, Emin C. Dogrul
Modeling software and documentation originated and maintained by the Bay-Delta Office, California Department of Water Resources, 1416 Ninth Street, Sacramento, CA 95814
http://baydeltaoffice.water.ca.gov/modeling/hydrology/c2vsim/index_c2vsim.cfm
This report describes version R374 of the C2VSim-CG model, released in June 2013.
This updated version of the report (version 1.1) was published in March 2016.

Table of Contents

List of tables

List of figures

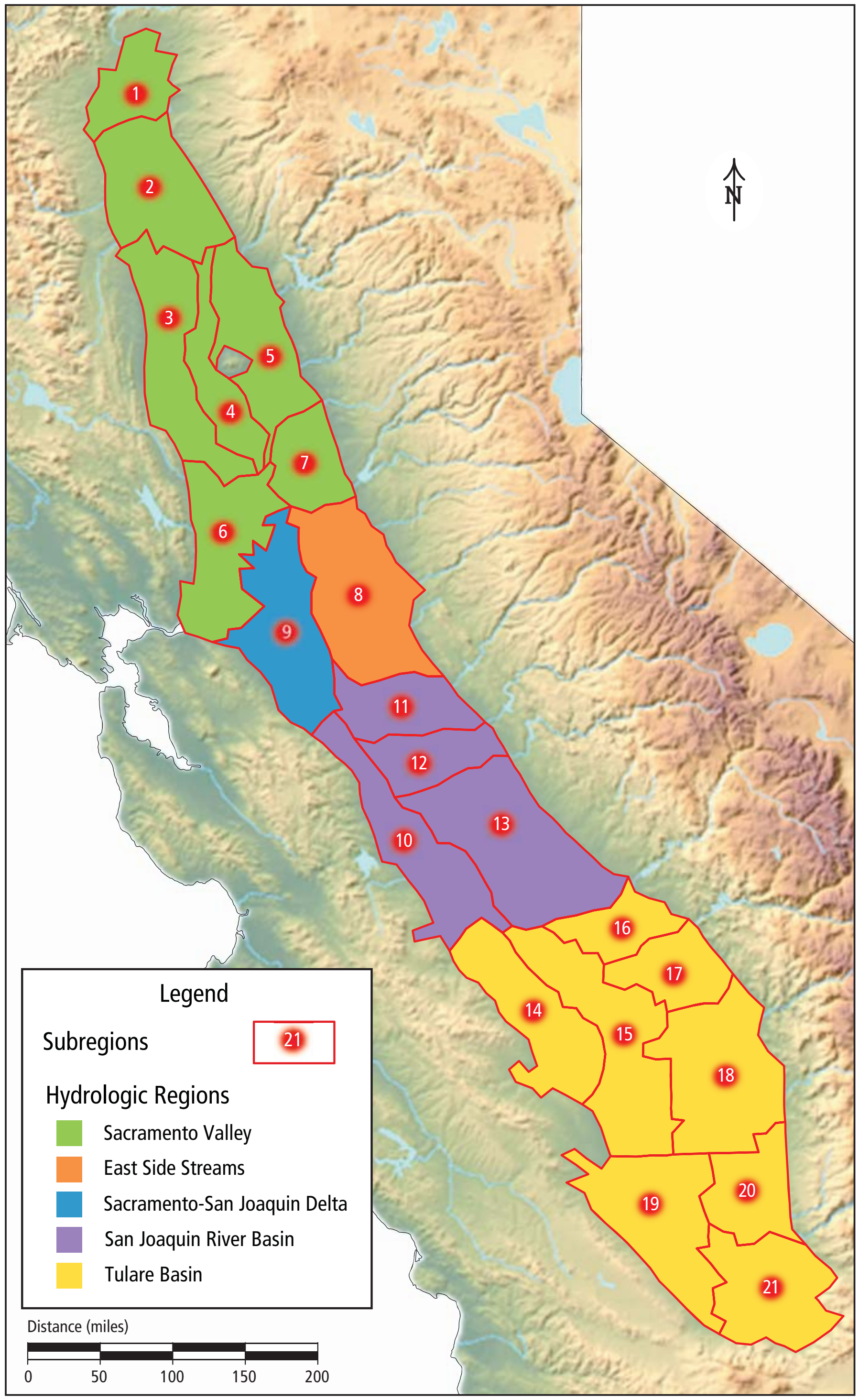
Acronyms and Abbreviations

Ag	Agricultural
C2VSim	California Central Valley Groundwater-Surface Water Model
CalSim	California Central Valley Project and State Water Project Operations Model
CCWD	Contra Costa Water District
CFS	Cubic Feet per Second
CN	Curve Number
CN*	Modified Curve Number
CVGSM	Central Valley Groundwater-Surface Water Model
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act
CWEMF	California Water and Environment Modeling Forum
DAU	Depletion Analysis Unit
DSA	Decision Support Area
DSS	U.S. Army Corps of Engineers Hydrologic Engineering Center's Data Storage System
DWR	California Department of Water Resources
EIR	Environmental Impact Report
EIS	Environmental Impact Statement
ET_C	Crop Evapotranspiration Rate
GIS	Geographic Information System
GPCG	Generalized Preconditioned Conjugate Gradient numerical solution method
GUI	Graphical User Interface

HEC	U.S. Army Corps of Engineers Hydrologic Engineering Center
HR	Hydrologic Region
IGSM	Integrated Ground-Surface Water Model
IWFM	Integrated Water Flow Model
MAF	Million Acre-Feet per Month
ME	Mean Error
NERSC	U.S. Department of Energy National Energy Research Scientific Computing Center
NRCS	U.S. Department of Agriculture Natural Resources Conservation Service
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RMSE	Root Mean Squared Error
SANJASM	U.S. Bureau of Reclamation San Joaquin Study Area Simulation Model
SOR	Single Over-Relaxation numerical solution method
SR	C2VSim Model Subregion
SSURGO	U.S. Department of Agriculture Natural Resources Conservation Service Soil Survey Geographic Database
STATSGO	U.S. Department of Agriculture Natural Resources Conservation Service U.S. General Soil Map
SWP	California State Water Project
SWRCB	California State Water Resources Control Board
TAF	Thousand Acre-Feet per Month
USACOE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WWD	Westlands Water District

Introduction

Figure 1. C2VSim model subregions and hydrological regions.



This report describes the input and output files for the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim). C2VSim is an integrated numerical model simulating land surface processes and groundwater and surface water flows in the main alluvial aquifer system of California's Central Valley (figure 1). C2VSim was developed using the Integrated Water Flow Model (IWFM) application, which couples a three-dimensional finite element groundwater simulation process with one-dimensional land surface, stream flow, lake, unsaturated zone and small-stream watershed simulation processes. The C2VSim version described in this report runs under IWFM version 3.02 and utilizes a coarse grid, and is thus referred to as version 3.02-CG. In addition, the input files for the C2VSim model are regulary updated to correct errors, incorporate imroved input data or extend the simulation time period. These updates are referred to as revisions; this report describes the data in revision R374, released in June 2013.

The C2VSim model inputs include monthly historical precipitation, stream inflows, surface water diversions, land use and crop acreages for the simulation period, October 1921 through September 2009. C2VSim dynamically calculates crop water demands, allocates contributions from precipitation, soil moisture and surface water diversions, and calculates the groundwater pumpage required to meet the remaining demand. The coarse grid version of the C2VSim model incorporates a finite element grid with 1392 elements, grouped into 21 water budget subregions (figure 1), which are further grouped by drainage basin into five hydrologic regions. The model subregions are based on Depletion Study Areas (DSAs), originally created by the DWR Division of Planning for estimating regional water supplies and demands. Hydrologic parameters (including hydraulic conductivities, storage parameters and recession coefficients) were calibrated to match observed values including groundwater heads, groundwater head differences between well pairs, surface water flows, and stream-groundwater flows for the period between September 1975 and October 2003.

The model simulates the historical response of the Central Valley's groundwater flow system to historical stresses, and can also be used to simulate the response to projected future stresses. Agricultural groundwater pumping is not monitored in the Central Valley, and the C2VSim model provides pumpage estimates that are considered robust because they are constrained spatially and temporally by the estimated demand and surface water supplies. The calibrated model is also being used as the basis for the groundwater flow component of CalSim 3, a water resources planning model for simulating operation of the California State Water Project (SWP) and Federal Central Valley Project (CVP).

Acknowledgements

Many people were involved in the development of the C2VSim model. Management support for development of the C2VSim model was provided by Kathy Kelly, Francis Chung, Sushil Arora and Tariq Kadir of DWR, and administrative support was provided by Sina Darabzand and Rich Juricich of DWR and Robert Leaf of CH2M Hill. Numerous DWR staff contributed to the development of the C2VSim model, including Michael Moncrief (currently with MBK Engineers), Guobiao Huang, Jane Shafer-Kramer, Messele Ejeta, and Liheng Zhong of the Bay-Delta Office, and Linda Bond, Chris Bonds, Dong Chen, Jeff Galef, Todd Hillaire, Abdul Khan, Seth Lawrence, Dan McManus, Paul Mendoza, Chris Montoya, Robert Niblack, Scott Olling, Eric Senter, Steven Springhorn, Jean Woods, Brett Wyckoff.

Surface water diversion data were provided by Andy Draper of MWH Global, Robert Barbato and Peter Arpin of the U.S. Army Corps of Engineers, Ben Bray of East Bay Municipal Utility District, Terry Erlewine of the State Water Contractors, Andy Florentino of Solano County Water Agency, Clifton Lollar of the Kings River Water Association, Mark McClintock of Carmichael Water District, Sue Sindt of Nevada Irrigation District, and Max Stevenson of Yolo County Flood Control and Water Conservation District. Lee Bergfeld and Water Bourez of MBK Engineers reviewed the input data sets and advised on their improvement. Charles Burt, Beau Freeman, Dan Howes, Sierra Orvis and Stuart Styles of the Irrigation Training and Research Center at California Polytechnic State University at San Luis Obispo reviewed the input data and output values related to simulated evapotranspiration rates. Claudia Faunt of the U.S. Geological Survey provided subsidence observations used in model calibration.

C2VSim is based on the CVGSM model, which was supplied by Saquib Najmus and Ali Taghavi of RMC-WRIME. Steve Shultz of CH2MHill performed the initial phases of model calibration, with assistance from Dan Wendell (currently with The Nature Conservancy) and Peter Lawson. Matt Tonkin of S.S. Papadopoulos and Associates (SSPA) assisted in developing tools to link the IWFM application with PEST, and Gilbert Barth of SSPA provided assistance developing pilot points. John Doherty of Watermark Numerical Computing provided advice on running PEST and transforming observations, and Willem Schreüder of Principia Mathematica and Velimir Vesselinov of Los Alamos National Laboratories provided invaluable advice on the BeoPEST software

Updates

C2VSim 3.02-CG release R374 incorporates several changes from the previous release.

- The Kings River bifurcation was changed so water naturally flows to the North Fork Kings River and a bypass routes flows to the South Fork Kings RIver. These changes were implemented in the Preprocessor file CVrivers.dat and the Simulation file CVdivspec.dat.
- Surface water diversion data for the Kings River in file CVdiversions.dat were modified. In the December 2012 release of C2VSim, winter agricultural diversions from the Kings River and flows reaching the end of the South Fork Kings were assumed to be recharged through aquifer storage and recovery (ASR) programs. These were modified so ASR diversions only occur upstream of the Kings River bifurcation, and the South Fork Kings River discharges to Tulare Lake. Surface water diversion volumes for water years 1981 through 1993 were also replaced with values from Kings River Watermaster Reports.
- Several parameters were modified to better simulate observed conditions. The diversion specifications for diversion 6 in file CVdivspec.dat were modified. The curve numbers for small-stream watersheds bordering model subregion 1 were increased and the maximum fraction of excess soil moisture that becomes deep percolation for subregion 1 was set to 0.250 in file CVparam.dat.

The IWFM Application

The C2VSim model uses version 3.02 of the Integrated Water Flow Model (IWFM) application (Dogrul 2012A, 2012B, 2012C). IWFM is a data-driven, comprehensive hydrologic application coupling a three-dimensional finite-element simulation of saturated groundwater flow with one-dimensional simulations of land-surface hydrologic processes, surface-water flow, lakes, vertical unsaturated-zone flow, and ungaged watersheds adjacent to the model boundary. IWFM is comprised of four applications, which are executed sequentially: Preprocessor, Simulation, Budget and Z-Budget. The Preprocessor application assembles the model framework, including the finite element grid, streams, lakes, precipitation stations, and land surface properties. The Simulation application performs a transient simulation, reading input data sets and calculating water flows through the land surface process, groundwater flow system and surface water system for each time step. The Simulation application produces groundwater and surface water hydrographs at user-specified locations, and stores information in binary and text files for post-processing. Binary files produced by the Simulation application are used by the Budget application to produce process-level budgets for each model subregion, and by the Z-Budget application to produce detailed budgets for groundwater 'zones' which the user can define. Text files of groundwater heads and subsidence at each node produced by the Simulation application can be used by the TecplotTM (Tecplot, Inc. 2011) program to produce movies of changes in aquifer heads through time. The IWFM GIS/GUI tool can create ArcMapTM (Esri Inc., 2012) shapefiles from model input files, and can produce MS Excel files from binary output files. IWFM documentation, executables, source code and utility applications are available from the DWR web site by following the link http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/.

Groundwater

The groundwater flow system is modeled as a multilayer aquifer system with a mixture of confined and unconfined aquifers separated by confining layers. Horizontal and vertical groundwater flow are simulated using the Galerkin finite element method and a quasi-three-dimensional approach utilizing the depth-integrated groundwater flow equation for horizontal flows in each aquifer layer and leakage terms for vertical flow between aquifer layers. In IWFM, groundwater pumping rates can be specified in two ways: the pumping rate can either be specified for each subregion and distributed to elements in that subregion, or individual wells can be specified and the pumping rate can be assigned to each well

Land surface

The IWFM land surface process computes economic water budgets (balancing inflows and outflows) for each of four land use categories: agricultural, urban, native and riparian. The land-surface process computes infiltration and runoff from precipitation using the NRCS curve number method (U.S. Department of Agriculture, 2004A); consumptive water use by irrigated crops, urban areas and native vegetation; infiltration and return flows from surface water diversions and groundwater pumping; and recharge to the unsaturated zone. Surface water and groundwater are dynamically allocated to meet agricultural and urban demands, runoff is routed to streams and deep percolation is routed to the unsaturated zone. The land surface process can also dynamically adjust the groundwater pumping rate upward and downward to exactly match any agricultural and urban demands that remain after using surface water diversions.

Within IWFM, the term runoff refers to precipitation that does not infiltrate and flows to rivers, and the term return flow refers to irrigation water that does not infiltrate and flows to rivers. The precipitation file contains time series precipitation for each model element. At runtime, IWFM uses the hydrologic soil group of each model element to select the curve number that is used to partition precipitation between infiltration and runoff. Hydrologic soil group A, with low runoff potential, consists mainly of deep, permeable and well-drained sands and gravels. Hydrologic soil group B, with low to moderate runoff potential, consists of soils with moderately fine to moderately coarse textures that are moderately to well drained. Hydrologic soil group C, with moderate to high runoff potential, consists of soils with moderately fine to fine texture, often with a clay layer that impedes drainage. Hydrologic soil group D, with high runoff potential, consists mainly of clay soils with high swelling potential, shallow soils over nearly impervious materials, and soils with a high permanent water table. Sixteen runoff curve numbers are entered for each model subregion: one curve number for each of the four hydrologic soil groups for each of the four land use types. Each land surface element is given a hydrologic characteristic value between 1.0 (for A) and 4.0 (for D) that is calculated as the area-weighted average of the hydrologic soil group values from the NRCS soil maps (U.S. Department of Agriculture, 1997, 2004B). Rainfall runoff is routed from each element to the specified stream node, and infiltrated rainfall enters the root zone.

Infiltrated rainfall and evapotranspiration are used to calculate irrigation demand. The evapotranspiration file contains time-series crop evapotranspiration (ETc) data for each crop, each non-agricultural land use, and bare soil for each subregion. The water budget process uses crop acreages and evapotranspiration rates to determine total water demand, and subtracts available root zone soil moisture (from infiltrated rainfall from the current time step plus the residual soil moisture from the previous time step). For agricultural and urban land uses, the difference between total water demand and the available soil moisture is used to determine irrigation demand, which is then met with surface water diversions and groundwater pumping. At the end of each time step, if the water stored in the root zone is greater than the storage capacity, this is apportioned between return flows and deep percolation.

Unsaturated zone

The unsaturated zone extends from the bottom of the plant root zone to the water table, which is the top of the saturated portion of the groundwater flow system. IWFM only simulates downward vertical water movement in the unsaturated zone; owing to the large difference between horizontal and vertical distances within each model element, horizontal movement of soil moisture is assumed to be negligible compared to the vertical movement. The unsaturated zone can be divided into multiple layers, with vertical hydraulic conductivity and porosity parameters assigned to each element and layer. Moisture traveling from the root zone into the unsaturated zone is termed deep percolation, and moisture travelling from the unsaturated zone to the groundwater is termed net deep percolation in the IWFM budget tables.

Surface Water Flow Network

Surface water flow is simulated using one-dimensional line elements comprising river segments. The surface-water flow network is described by river nodes coincident with groundwater nodes, by river segments linking pairs of river nodes, and by river reaches formed of a contiguous group of river segments. Individual river segments can correspond to an element boundary or can cut across an element. Bed elevation and stage-flow relationships are specified for each river node in the pre-processor, and bed conductance is specified for each river node in the simulation parameter input file. Time-series of surface-water inflows at the model boundaries and surface-water diversion rates from individual river nodes are also specified in simulation input files. Surface-water flow at each river node is dynamically simulated as a function of inflow from upstream segments, tributaries, precipitation runoff, agricultural return flows, and urban return flows; outflows to diversions and the downstream river segment; lake and bypass inflows and outflows; and exchanges with the groundwater flow system.

Small-stream Watersheds

The IWFM small-stream watersheds process simulates overland and subsurface flow from ungaged watersheds adjacent to the model boundary. Eight parameters control how precipitation is partitioned between infiltration and overland flow, and how groundwater is stored and is discharged to the ephemeral stream and laterally into the groundwater flow system. The simulation parameter file has soil characteristics, hydraulic conductivity, curve number and recession coefficients used to calculate surface runoff and groundwater recharge for each small-stream watershed. The simulation boundary conditions input file has the watershed area, the groundwater node receiving subsurface flows, the groundwater nodes along the surface flow path to the river node receiving precipitation runoff, and the river node number.

Lakes

The IWFM lake process simulates lakes comprising one or more model elements. Lakes receive surface water from one or more rivers, upstream lakes, and bypasses, and discharge surface water to a downstream lake or to a river node. Lakes can also exchange water with the groundwater using a lake-bed conductance, and can interception water from precipitation, and lose water to evaporation. The maximum lake elevation is specified as a time series.

Input Data

IWFM is a data-driven application in which simulations utilize both static data and time-series data. Depending on the information type, data can be specified by node, element or subregion. Much of the static data describing the model framework is compiled by the IWFM preprocessor, and some, such as the parameters and the small-stream watershed descriptions, is specified in the boundary conditions file.

In an IWFM model, the model domain is divided into subregions, groups of contiguous model elements. These subregions are used for both data input and for the analysis of simulation results. Each model element, stream node, lake, etc. is assigned to a subregion, and each subregion operates as a 'virtual farm' for the calculation of crop water demands and the allocation of surface water and groundwater. The IWFM Budget application also provides water budget reports by subregion. Much of the model input data is organized by subregion and land use type, including curve numbers and minimum soil moisture parameters, crop acreages, urban water demand and groundwater pumping data.

IWFM initial conditions are supplied for each simulation. The initial conditions include the initial aquifer head, preconsolidation head and interbed thickness at each groundwater node; initial root-zone soil moisture conditions; initial unsaturated zone soil moisture conditions; initial soil moisture content and groundwater storage of each small stream watershed; and initial lake surface altitude for each lake.

Output

The IWFM Preprocessor application compiles the model grid into a binary file that is read by the Simulation application and writes a text-based output file describing the characteristics of the model grid. The IWFM Simulation application calculates state variable for each time step, including groundwater heads, stream flows, and the root-zone soil moisture. The Simulation application also produces binary files that are processed by the Budget and Zbudget applications and text-based files with time-series of the groundwater head, surface water flow, tile drain flow and subsidence hydrographs at user-specified locations. The Budget application produces text-based files with process-level budgets (including groundwater, land use, root zone and stream reach) for each model subregion, and the Zbudget application produces text-based files with detailed budgets for user-specified groundwater 'zones'.

Other Features

Other IWFM features include the incorporation of time-tracking for input and output data sets, linkage to the HEC-DSS database (U.S. Army Corps of Engineers Hydrologic Engineering Center, 2011) for both input and output, and a set of software utilities (IWFM-PEST utilities) for automated calibration using the PEST parameter estimation program (Doherty, 2004; CH2M Hill, Inc., and S. S. Papadopoulos and Associates, 2005). An IWFM GIS/GUI tool for ArcMapTM (Esri, Inc., 2010) can read the IWFM Preprocessor input files and construct shapefiles for the model framework. The IWFM Budget to Excel Tool reads Simulation program binary output files and creates MS Excel workbooks of the Budget tables. The Simulation application can also produce TecplotTM (Tecplot, Inc., 2011) files for viewing and animating head and subsidence maps for aquifer layers.

C2VSim Model Description

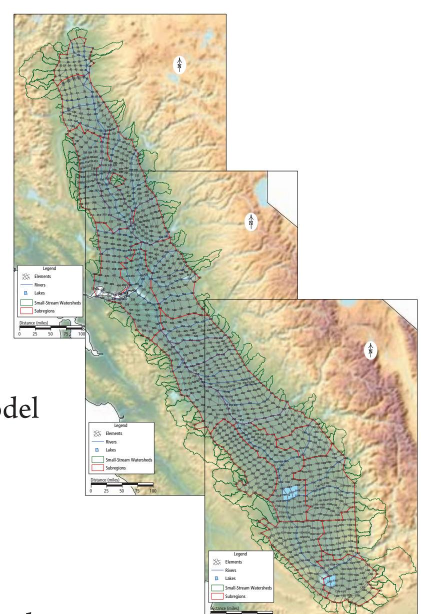
This section contains a general description of how the C2VSim model is constructed within the IWFM modeling framework. The basic C2VSim model was derived from the Central Valley Groundwater-Surface Water Simulation Model (CVGSM). The CVGSM model was developed in the 1980's by Boyle Engineering and James M. Montgomery Consulting Engineers with support from DWR, the U.S Bureau of Reclamation (USBR), the California State Water Resources Control Board (SWRCB) and the Contra Costa Water District (CCWD) (Boyle Engineering Company 1987; James M. Montgomery Consulting Engineers 1990A, 1990B). The CVGSM model was originally developed to simulate groundwater and surface water flows on a monthly time step from October 1921 to September 1980. The CVGSM model was improved and extended through 1990 (CH2M Hill, 1996), and was used to support the USBR Central Valley Improvement Project (CVPIA) Programmatic Environmental Impact Statement (U.S. Bureau of Reclamation, 1999).

The coarse grid version of the C2VSim model uses the finite element grid (nodes and elements) and water budget subregions of the CVGSM model. The stream network and aquifer layers of the CVGSM model were extensively refined for the C2VSim model. The CVGSM input data sets (land use, crop acreages, surface water inflows and diversions, etc.) also served as the basis for the C2VSim model, and were extensively reviewed, modified and refined to increase accuracy and detail, and extended through September 2009.

Model grid

The coarse grid version of the C2VSim model has a two-dimensional finite element grid composed of 1393 nodes forming 1392 elements covering an area of 19,710 mi2 (51,000 km2) (figures 2 and 3). The node locations are specified, and then the elements are defined according to the nodes at their corners. The three-dimensional groundwater model is defined by extending the two-dimensional grid of the basic C2VSim model vertically downward to form three aquifer layers. The surface water flow network is described by 449 river nodes (coincident with nodes of the two-dimensional finite element grid) grouped into 75 river reaches (figures 4 and 5). Surface water and groundwater from ungaged watersheds that encircle the Central Valley are simulated as inflow at the model boundaries for 210 small-stream watersheds (figure 6).

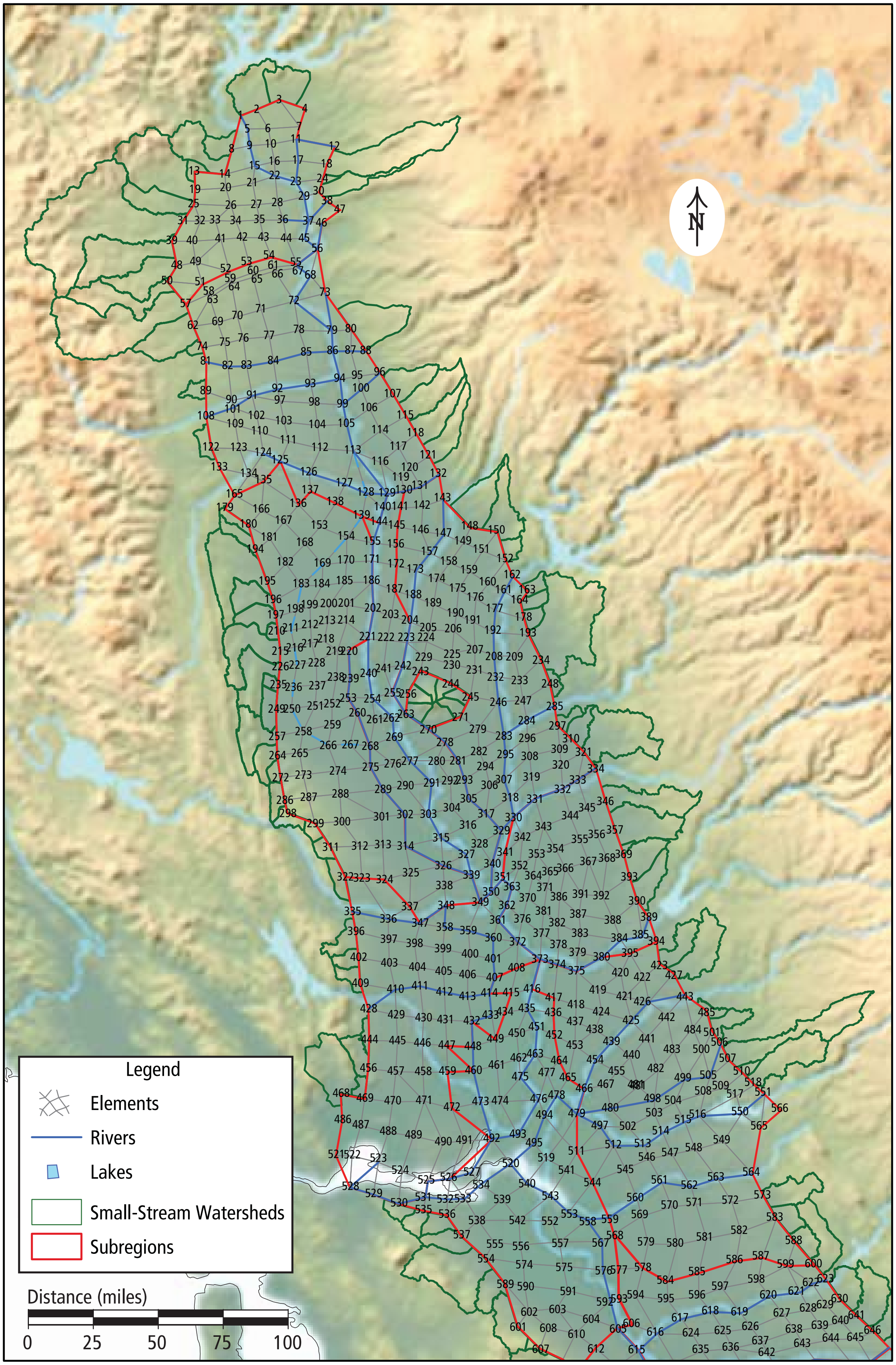
Figures 2a, 2b, and 2c overlapped (see following pages).



The finite element grid used in the coarse grid version of the C2VSim model was originally developed for the CVGSM model with the following features (James M. Montgomery Consulting Engineers, 1990B):

- the boundary of the two-dimensional finite element grid matches the boundary of the Central Valley alluvium;
- grid lines match streams and rivers included in the model, are parallel to the direction of stream flow, and incorporate the surface drainage pattern;

Figure 2a


N
Legend
Elements
Rivers
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0 25 50 75 100

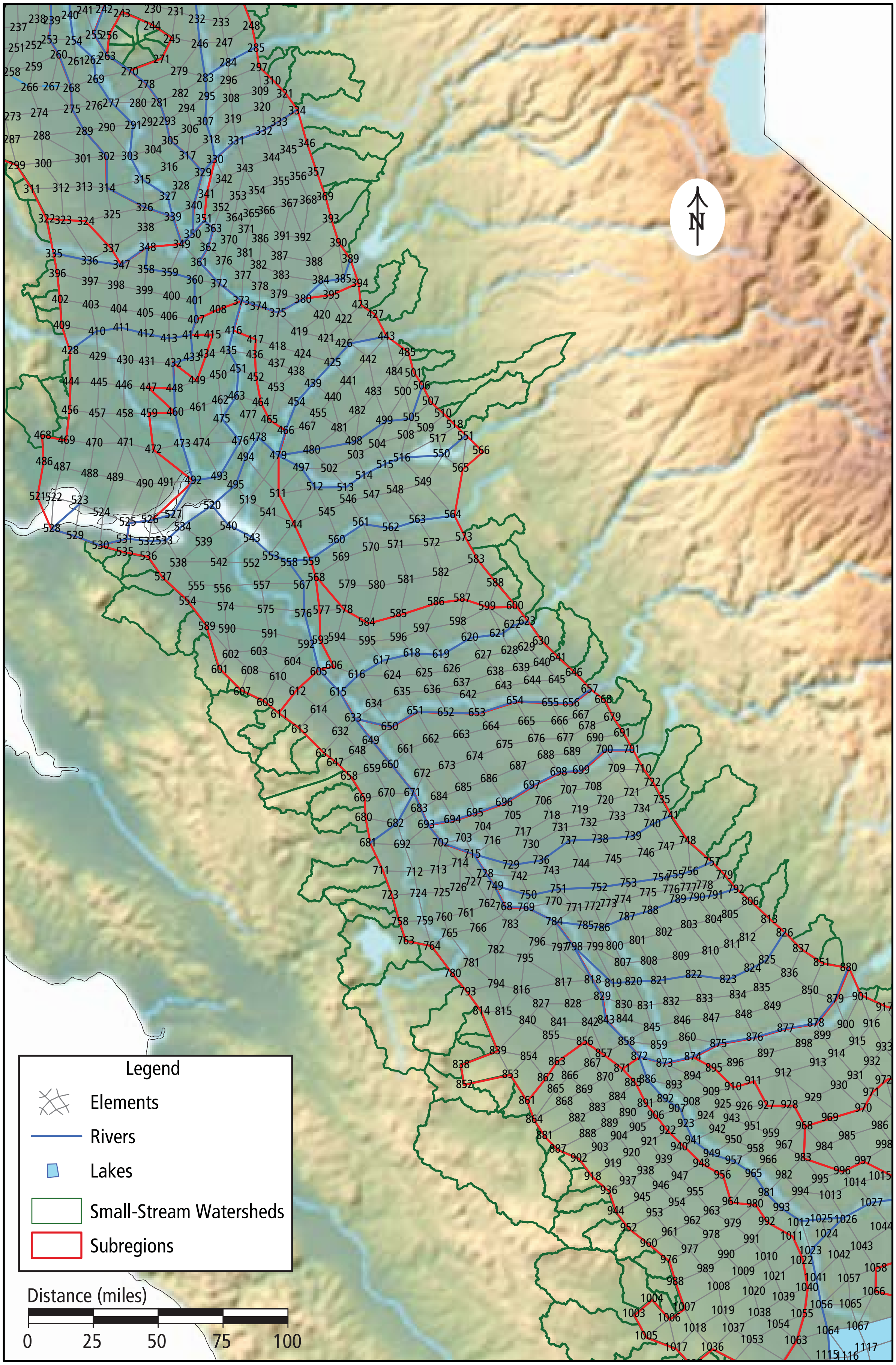

N
Legend
Elements
Rivers
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0
25
50
75
100

Figure 2b

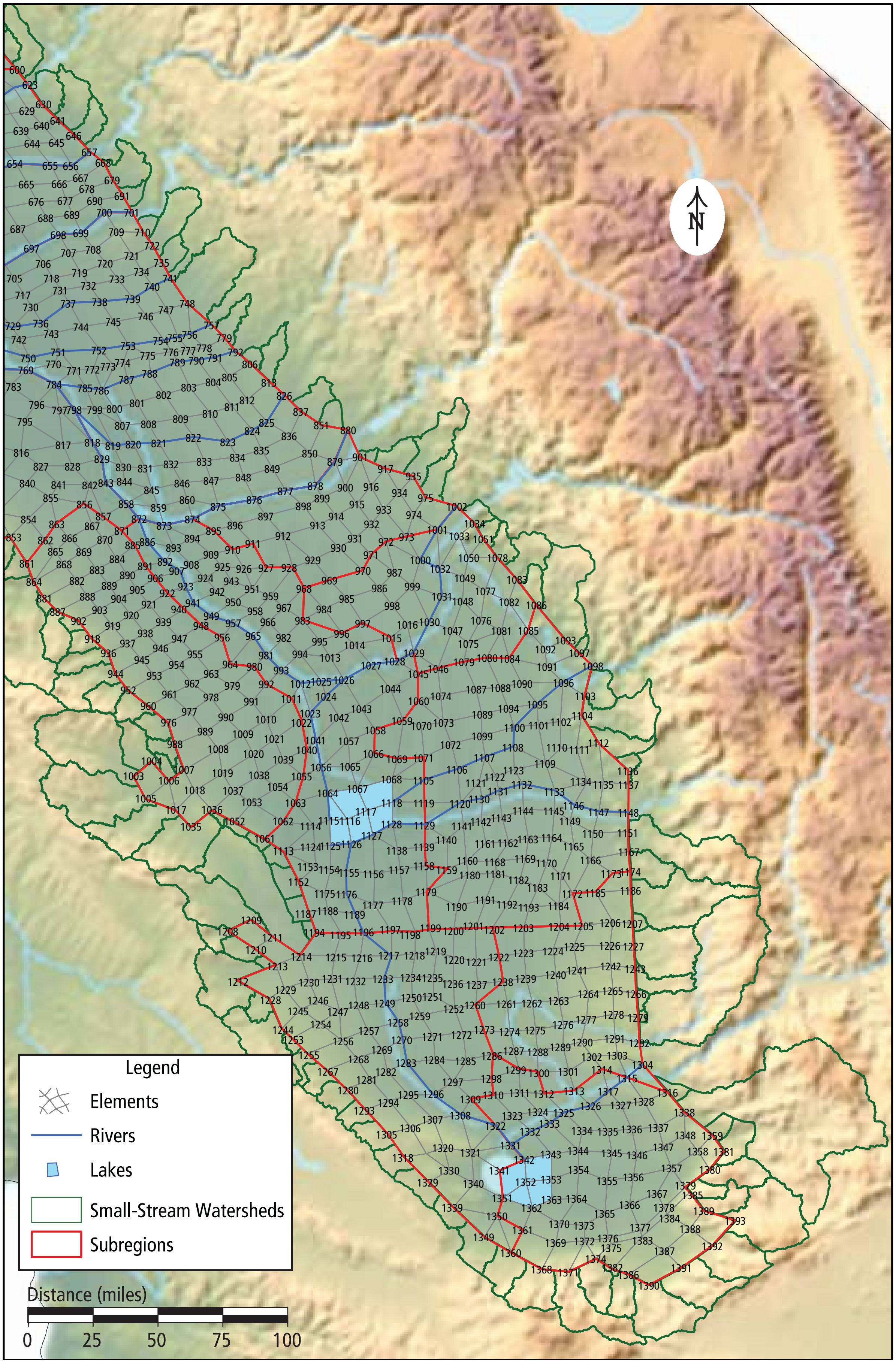

N
Legend
Elements
Rivers
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0
25
50
75
100

Figure 2c

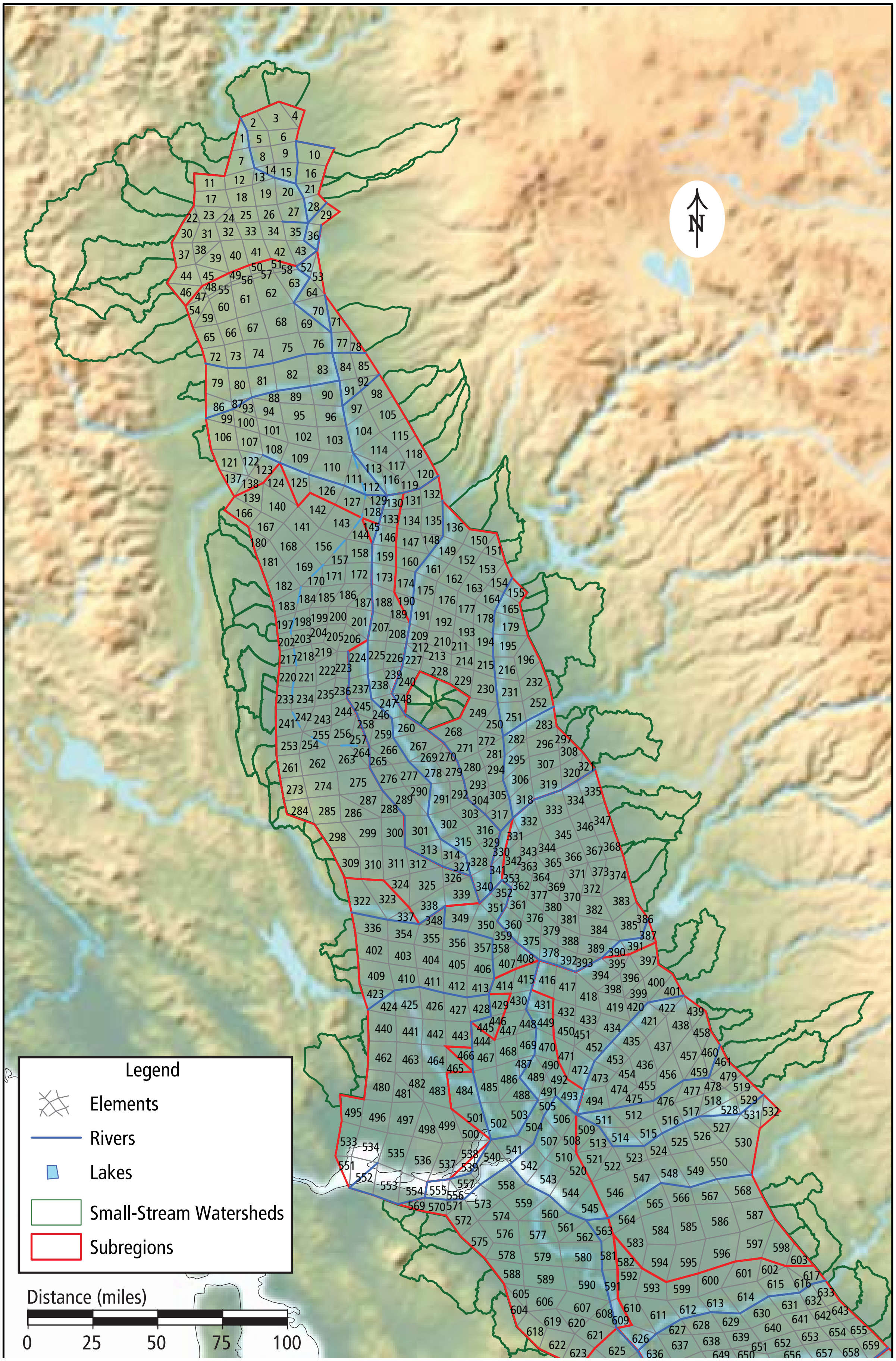
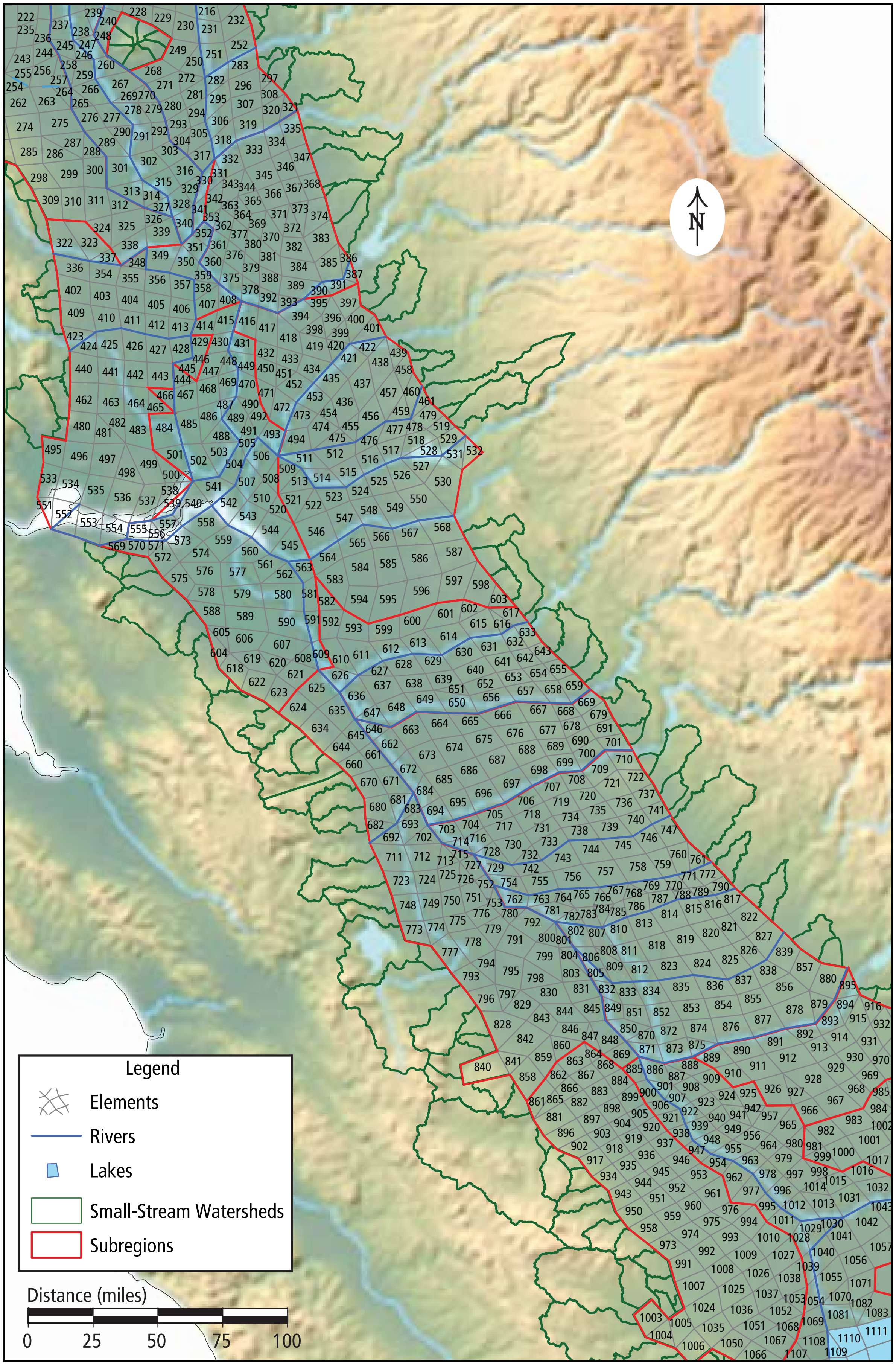

N
Legend
Elements
Rivers
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0
25
50
75
100

Figure 3a

Figure 3b


N
Legend
Elements
Rivers
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0
25
50
75
100

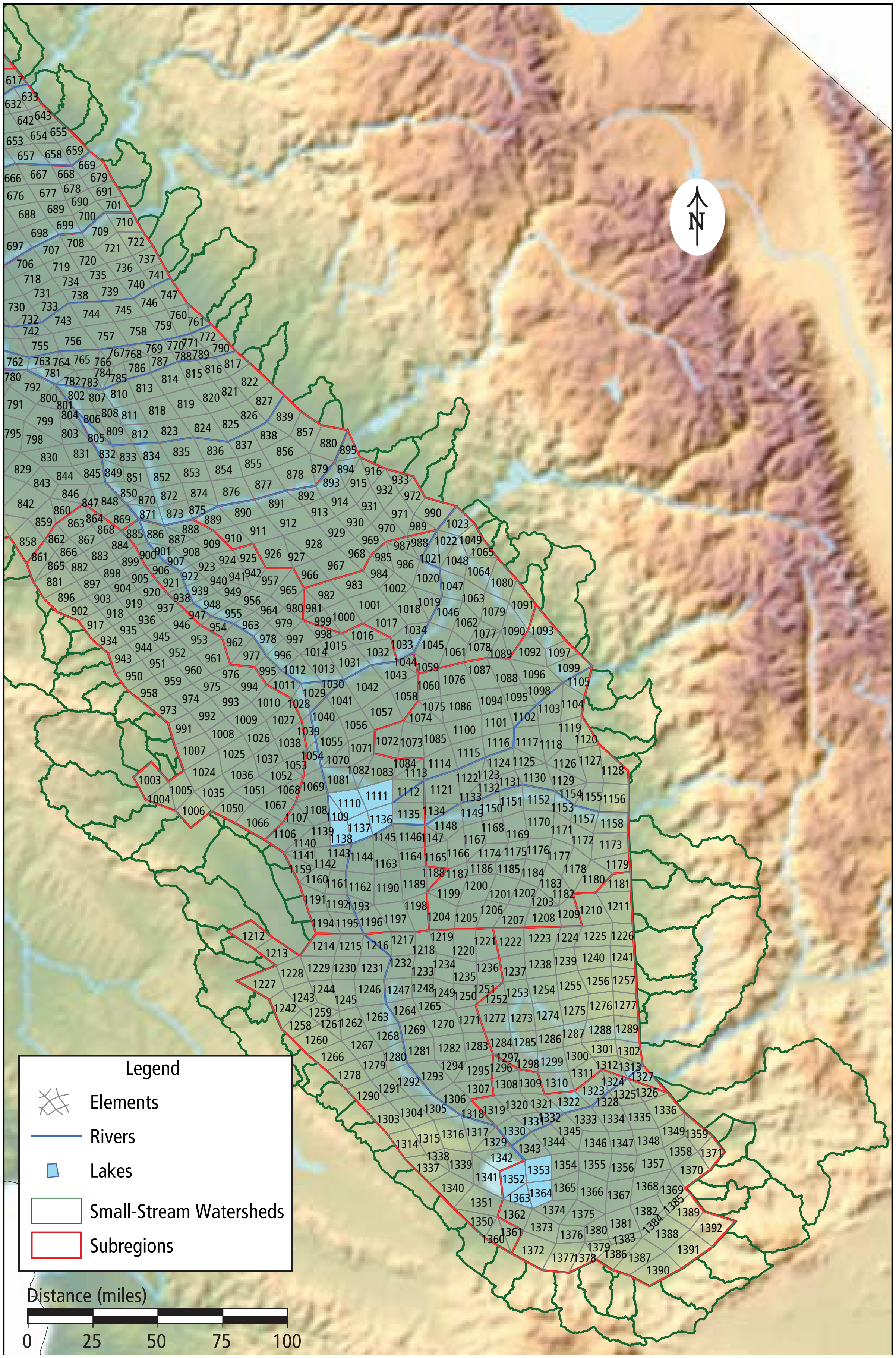
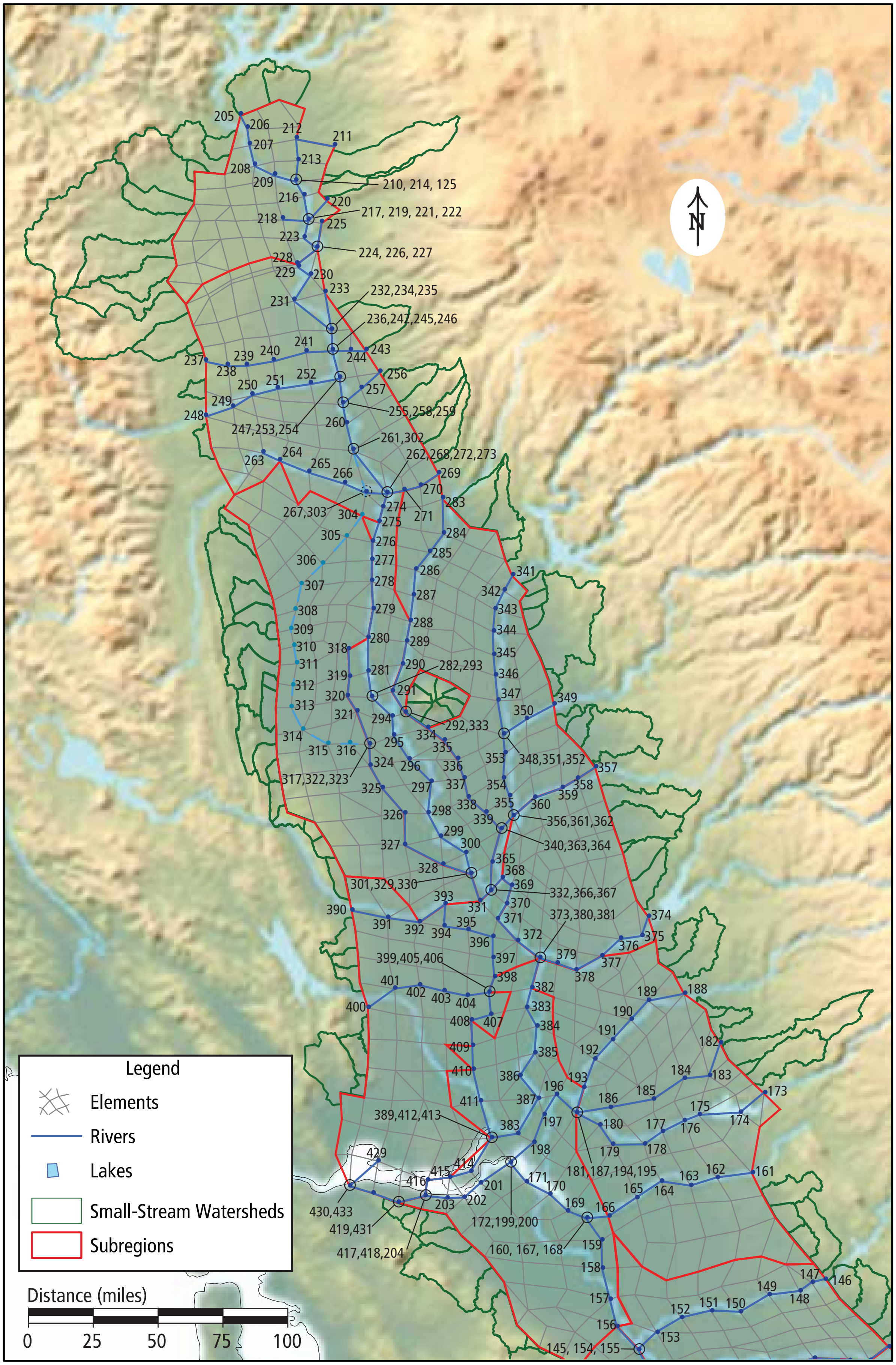

N
Legend
Elements
Rivers
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0
25
50
75
100

Figure 3c

Figure 4a


N
Legend
Elements
Rivers
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0
25
50
75
100

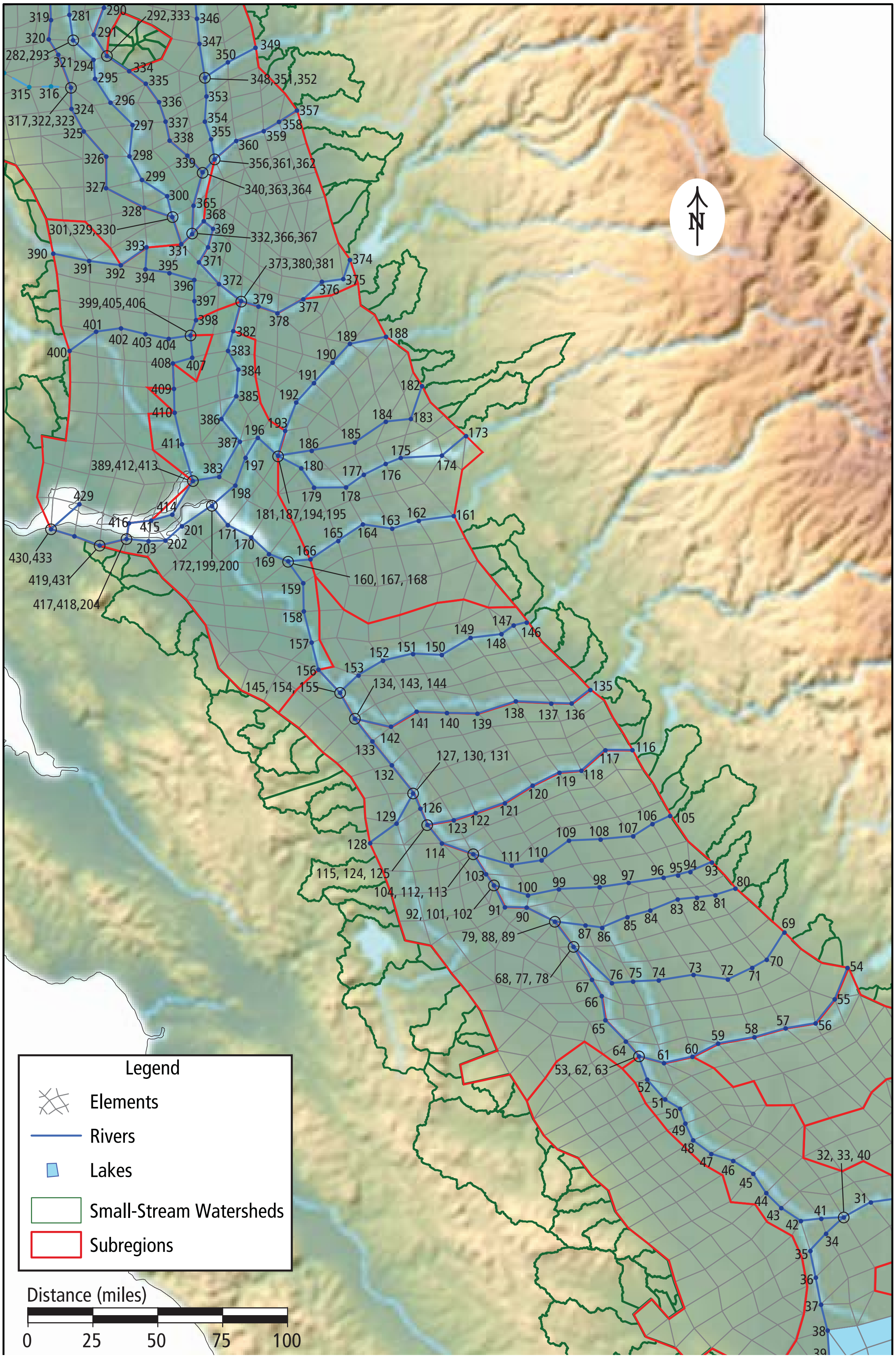
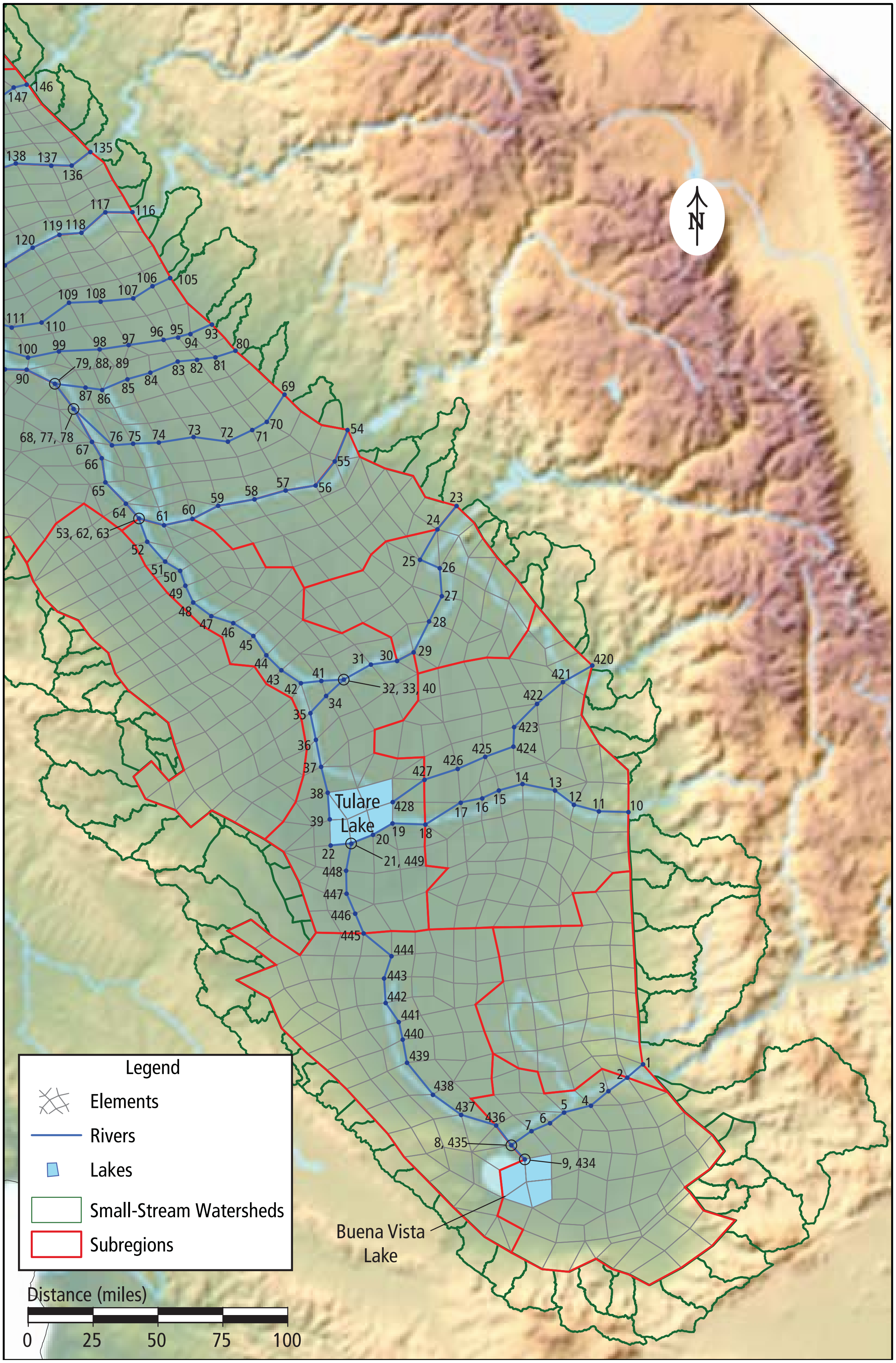

Legend
Elements
Rivers
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0
25
50
75
100
N

Figure 4b

Figure 4c


N
147
146
138
137
136
135
117
116
120
119 118
109
108
107
106
105
111
110
100
99
98
97
96
95
94
93
80
90
79, 88, 89
87
86
85
84
83
82
81
69
68, 77, 78
67
66
76
75
74
73
72
71
70
54
55
65
64
53, 62, 63
61
60
59
58
57
56
23
24
25
26
27
28
52
51
50
49
48
47
46
45
44
43
42
41
31
30
29
32, 33, 40
34
35
36
37
38
39
420
421
422
423
424
425
426
427
428
14
13
12
11
10
17
16
15
Tulare
Lake
19
18
20
22
21, 449
448
447
446
445
444
443
442
441
440
439
438
437
436
1
2
3
4
5
6
7
8, 435
9, 434
Buena Vista
Lake
Legend
Elements
Rivers
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0
25
50
75
100

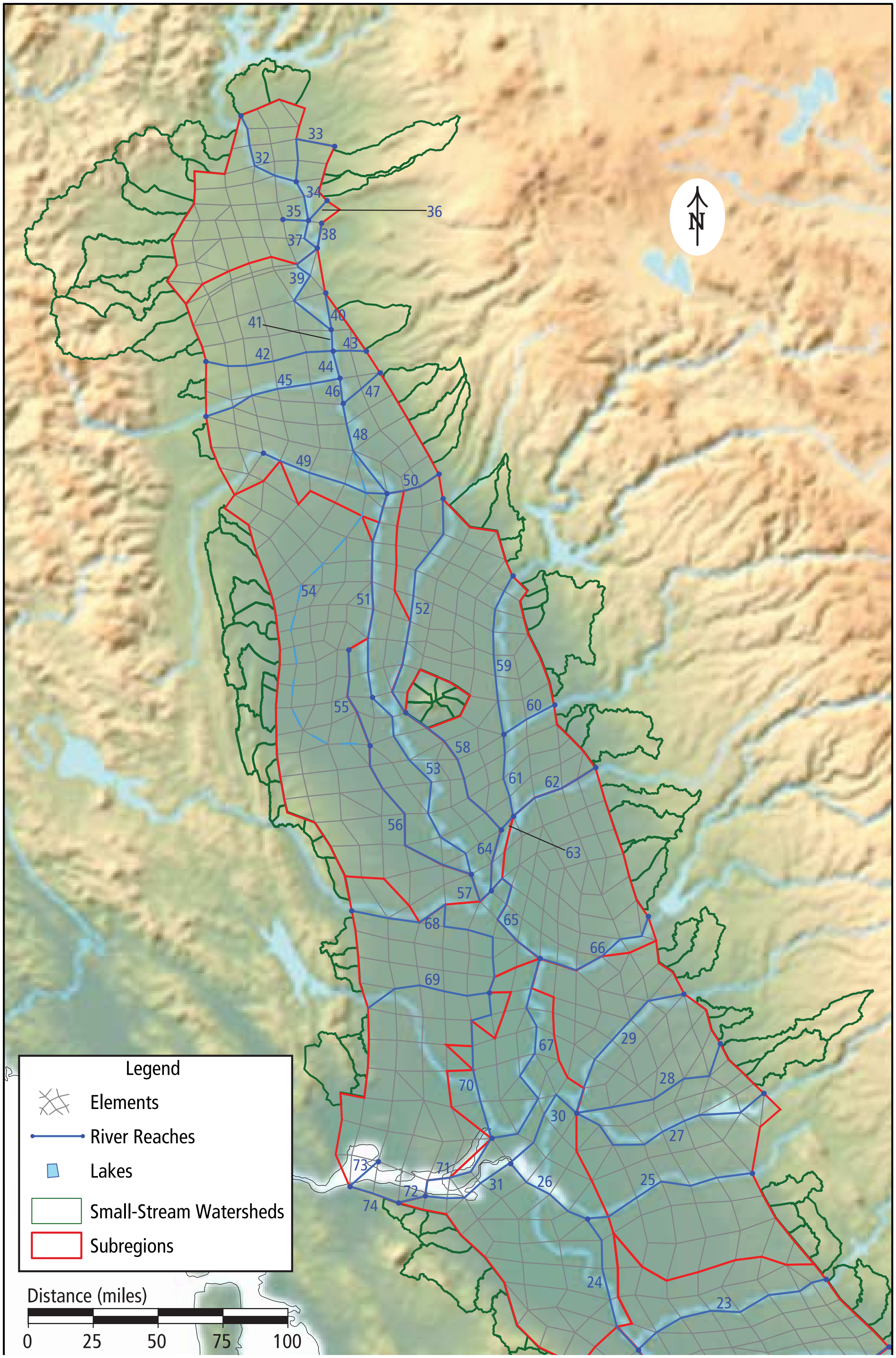
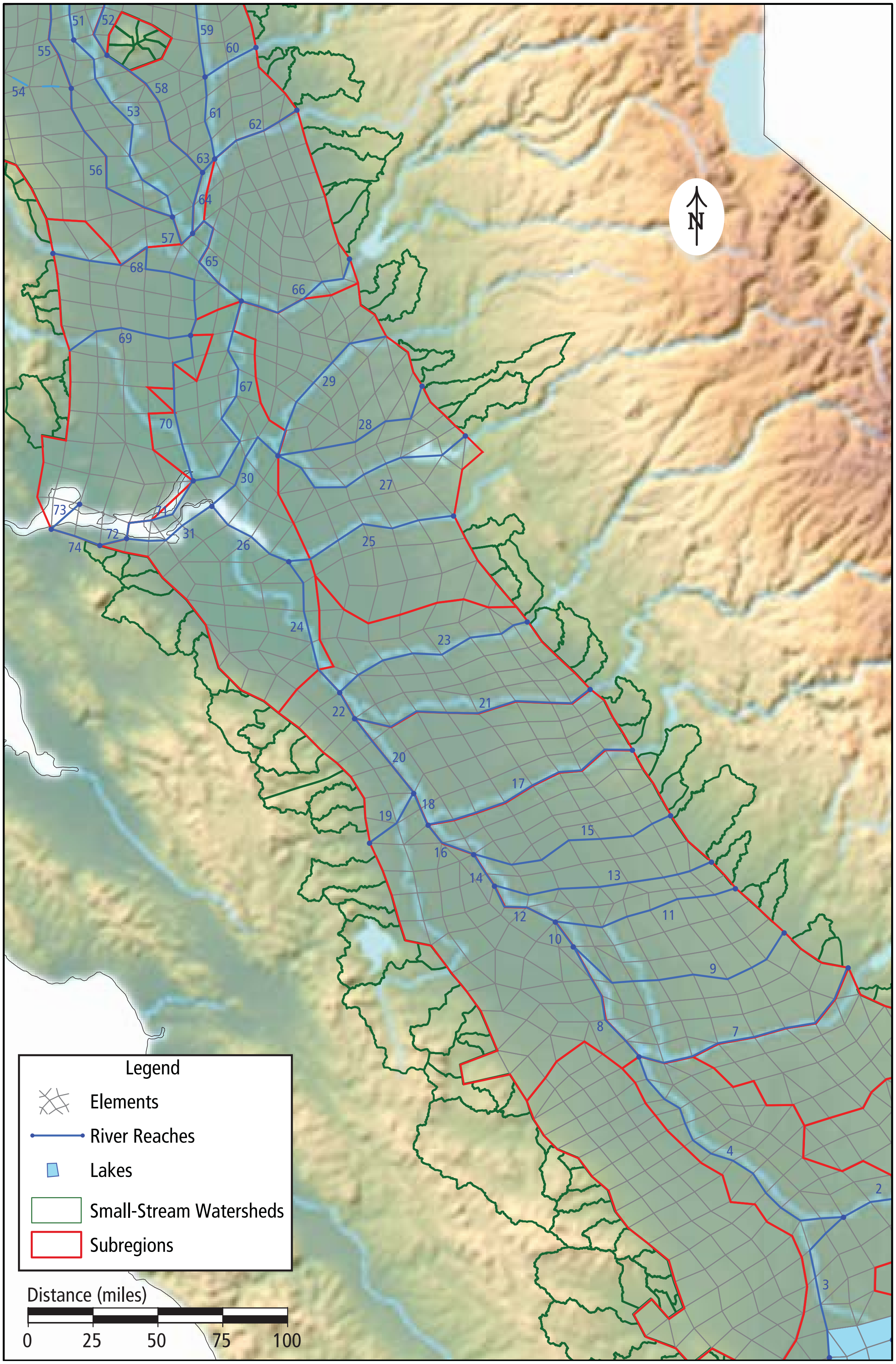

N
Legend
Elements
River Reaches
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0
25
50
75
100
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
31
30
29
28
27
26
25
24
23

Figure 5a

Figure 5b


N
Legend
Elements
River Reaches
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0
25
50
75
100

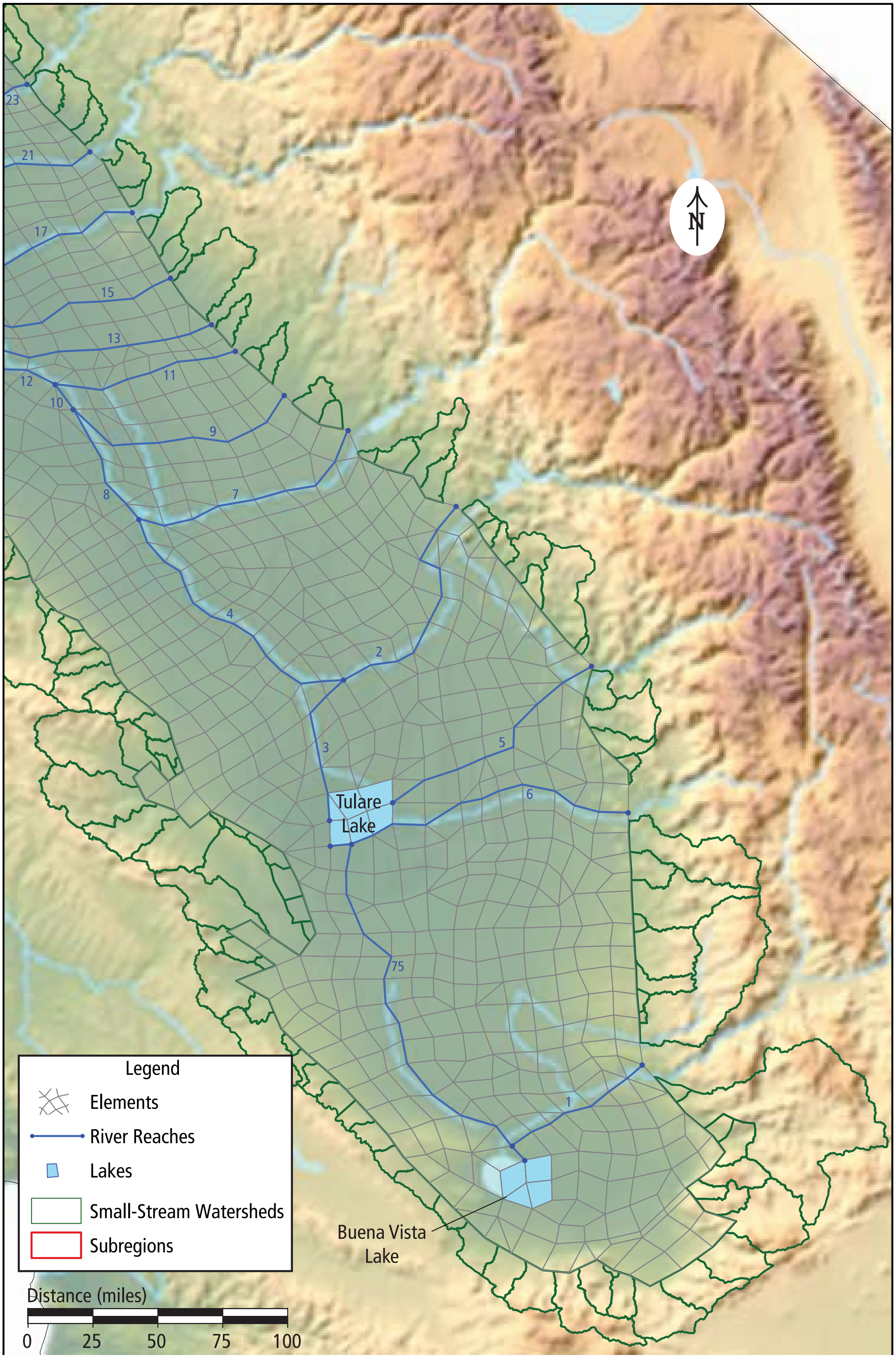
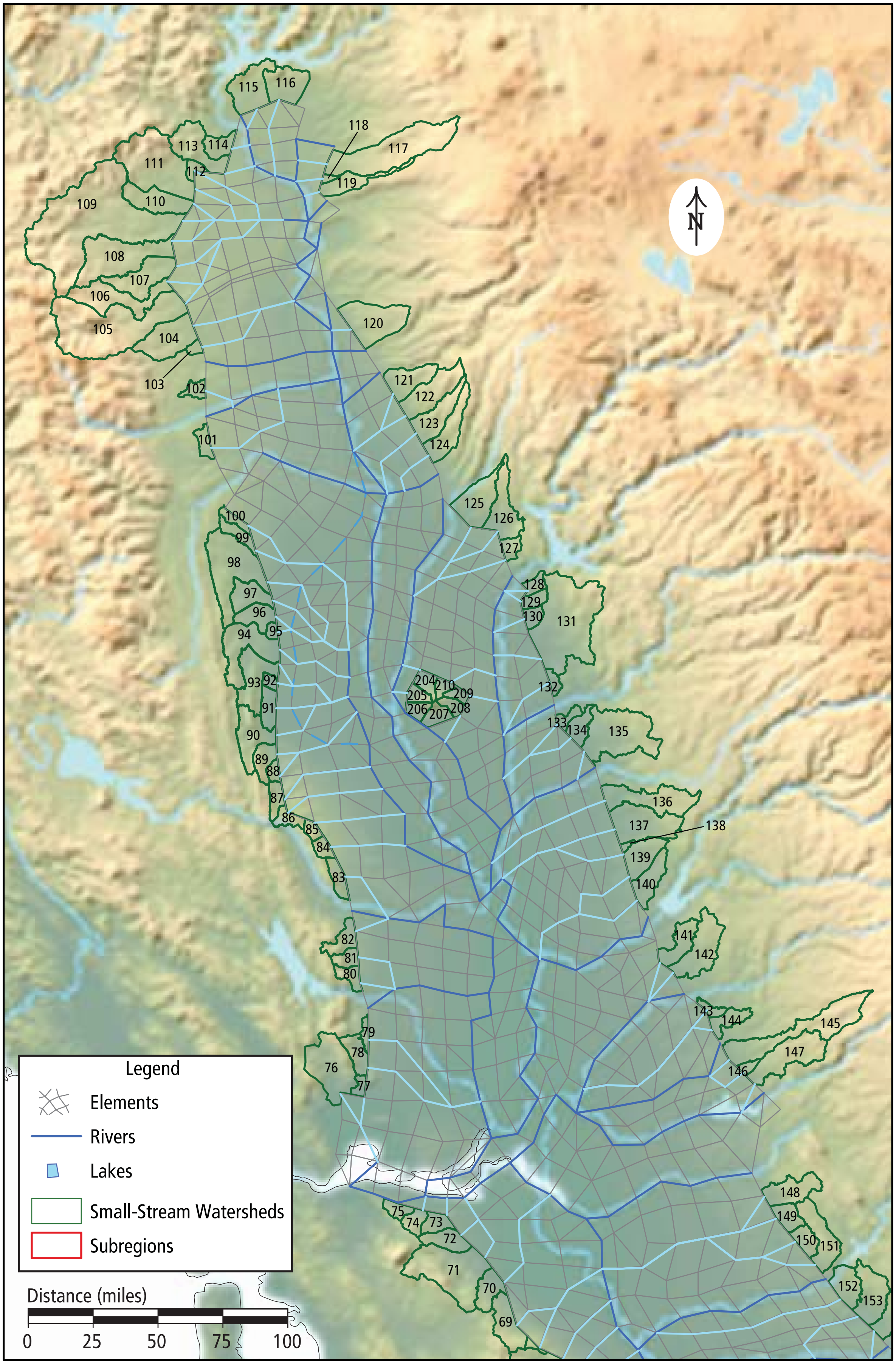

N
23
21
17
15
13
11
12
10
9
8
7
4
2
3
5
6
Tulare Lake
75
1
Buena Vista Lake
Legend
Elements
River Reaches
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0
25
50
75
100

Figure 5c

Figure 6a


Legend
Elements
Rivers
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0
25
50
75
100
N

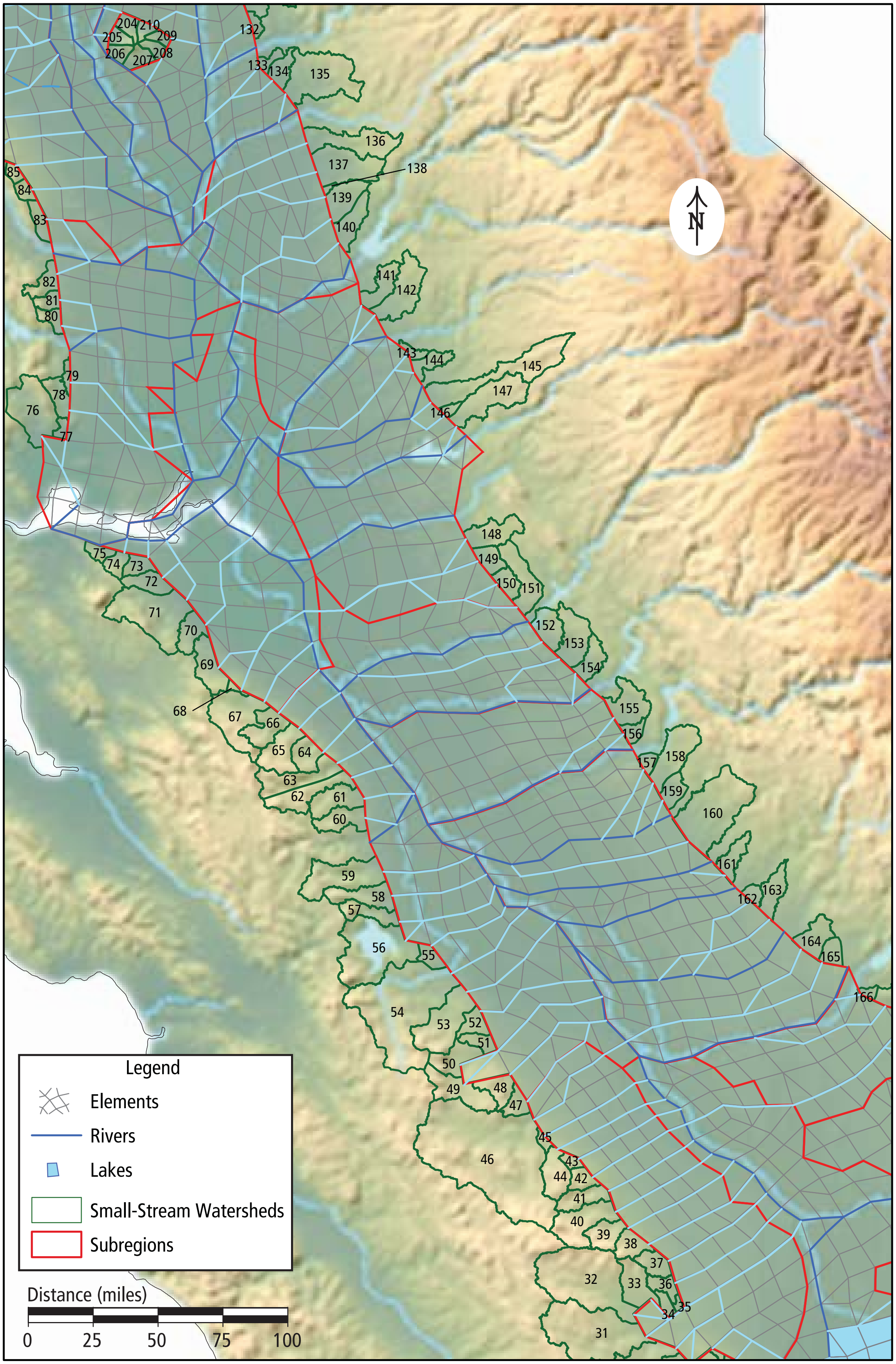
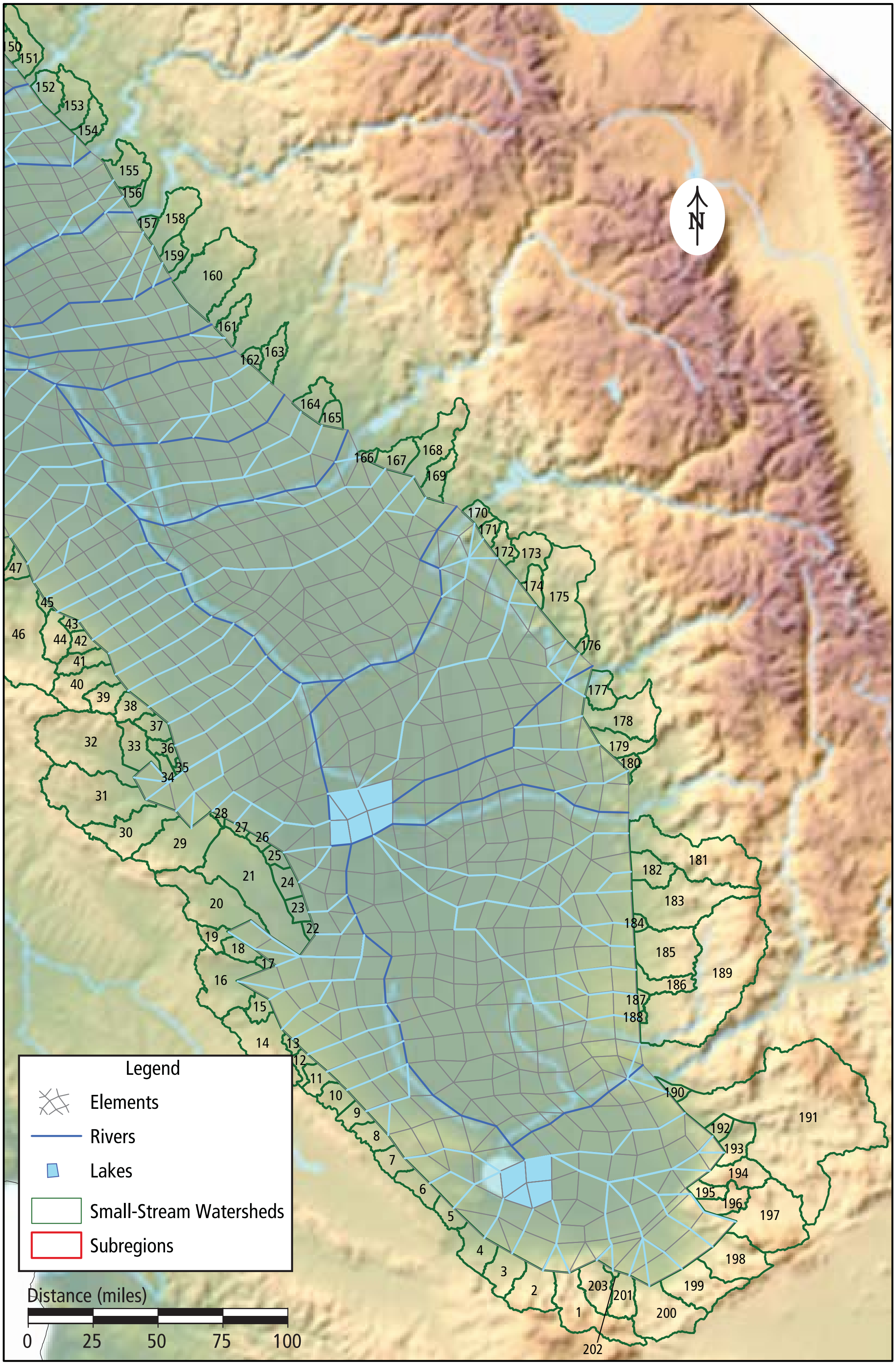

N
Legend
Elements
Rivers
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0 25 50 75 100
204 210 205 209 206 207 208 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166
85 84 83 82 81 80 79 78 76 77 75 74 73 72 71 70 69 68 67 66 65 64 63 62 61 60 59 58 57 56 55 54 53 52 51 50 49 48 47 46 45 44 43 42 41 40 39 38 37 36 35 34 33 32 31

Figure 6b

Figure 6c


Legend
Elements
Rivers
Lakes
Small-Stream Watersheds
Subregions
Distance (miles)
0
25
50
75
100
N

- the orientation of the grid generally follows inferred groundwater flow streamlines to incorporate the subsurface drainage pattern;
- element meshes are relatively finer in the vicinity of areas with steep groundwater gradients;
- thin strips of elements are included to incorporate discontinuous groundwater levels near major faults that create groundwater flow barriers; and
- element boundary lines match the predefined boundary lines of the 21 model subregions.

For the C2VSim model, the two-dimensional grid was retained, but the three-dimensional aquifer layering was significantly modified.

The model grid is defined by the nodal coordinates, and elements are then defined by connecting nodes to form either triangles or quadrilaterals. Model nodes are numbered in the two-dimensional grid, beginning at the northern end of the model domain and proceeding to the southern end. Nodal x-y coordinates were delineated with the origin arbitrarily set at the intersection of 35o N latitude and the 750,000 UTM line between 120o and 121o longitude, the x-axis collinear with the 35o N latitude line and the y-axis collinear with the 750,000 UTM line (James M. Montgomery Consulting Engineers, 1990B). The area of individual elements ranges from 2.1 mi2 (5.4 km2) to 33 mi2 (87 km2) and averages 14 mi2 (37 km2). Each element is allocated to one of the 21 model subregions (figure 1). These model subregions were originally defined in the CVGSM model (James M. Montgomery Consulting Engineers, Inc, 1990B), based on Depletion Study Areas (DSAs) originally created by the DWR Division of Planning.

Groundwater flow system

The fresh-water aquifer system of the Central Valley is simulated using three model layers. Model layer 1 represents the uncinfined portion of the aquifer, and model layers 2 and 3 represent the confined portions. In addition, groundwater pumping is confined to model layers 1 and 2, and model layer 3 generally represents the portion that is not pumped. The land surface altitude at each node was determined from topographic maps. The aquifer stratigraphy of the C2VSim model is based on the stratigraphy of the CVGSM model with some modifications. The stratigraphy in the CVGSM model was developed from 18 geologic cross sections based on extensive analysis of construction and geophysical logs from water, oil and natural gas wells; hydrologic and geologic maps; and existing reports and geologic cross sections (James M. Montgomery Consulting Engineers, 1990B), with local refinements based on additional data from the model of Williamson et al. (1985, 1989).

The aquifer stratigraphy was further modified for the C2VSim model by adjusting the bottoms of model layers 1 and 2 based on well screen information compiled from the DWR Water Well Library database, to apportion groundwater pumping from wells screened in the unsaturated zone to model layer 1 and wells screened in the confined zone to model layer 2, and no pumping occurs in model layer 3 (CH2M Hill, Inc., and S. S. Papadopoulos and Associates, 2006). In the area where the Corcoran Clay Member of the Tulare Formation is present, the bottom of model layer 1 and top of model layer 2 were adjusted to accommodate the observed altitude and thickness of this aquitard, which was also extended westward to intersect the model boundary. The bottom of model layer 1 was subsequently modified to facilitate model calibration by increasing the layer thickness to maintain a saturated depth of at least 100 ft (30.5 m) during model simulation, with minimum thicknesses of 10 ft (3.05 m) for model layers 2 and 3. The bottom of model layer 3 represents the bottom of the active fresh water aquifer, and was set equal to either the top of the basement complex (relatively impermeable igneous and metamorphic rocks and the Cretaceous Great Valley Sequence) or the base of fresh water (CH2M Hill and S. S. Papadopoulos and Associates, 2006). Model layer 3 generally corresponds to the unpumped fresh-water portion of the aquifer.

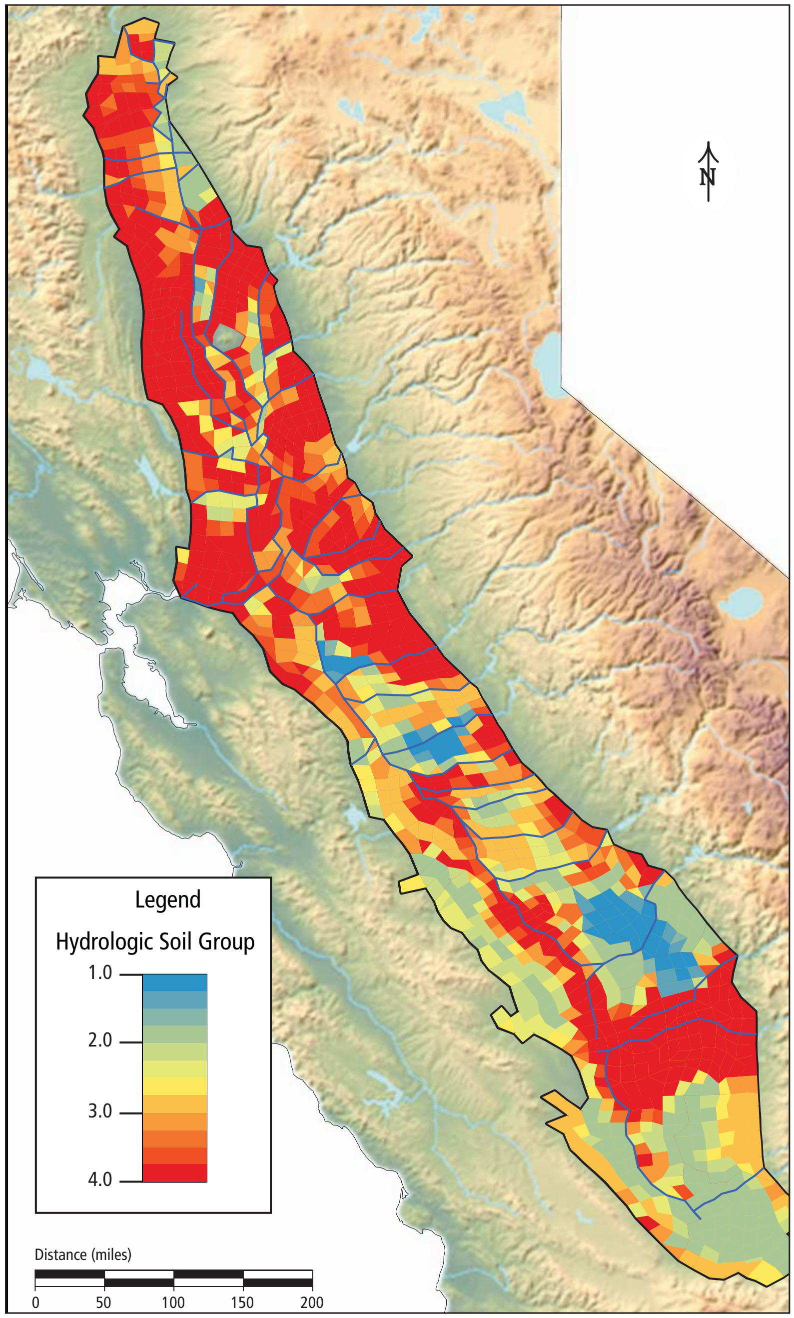
Groundwater pumping

The IWFM application reads specified groundwater pumping rates for each model subregion and each specified pumping well from an input file. A key feature of the IWFM application is that it can adjust the pumping rates so the water demands are exactly met with effective precipitation, surface water diversions and groundwater pumping. In California, agricultural groundwater pumping rates and some municipal groundwater pumping rates are generally not measured, and pumping rates are generally not published. This groundwater pumping adjustment feature is turned on for the C2VSim model, so the groundwater pumping volumes for C2VSim are calculated by the model. The spatial and vertical locations of agricultural wells and urban wells are specified at the start of the IWFM simulation phase and remain fixed throughout the simulation. The distribution of agricultural groundwater pumping changes during the simulation because agricultural pumping only occurs in model elements with some agricultural or municipal and industrial land use.

Land surface process

The IWFM land surface process calculates water demands, routes water from precipitation, surface water and groundwater to soil moisture, routes runoff and return flows to rivers, and routes deep percolation to the unsaturated zone. The calculations are performed for each model element in a root-zone layer above the three-dimensional finite element grid of the groundwater system. Land surface process data are entered in both the Preprocessor application and the Simulation application. The hydrologic soil group and the river node receiving runoff are specified for each model element in the Preprocessor input files. The river node receiving surface runoff from each element was determined for the CVGSM model by identifying watershed boundaries and surface water drainage direction from USGS topographic maps (James M. Montgomery Consulting Engineers, 1990B), and was reviewed and modified for the C2VSim model. Hydrologic soil properties for the C2VSim model (figure 7) were determined based on the SSURGO soil map coverage for the State of California (U.S. Department of Agriculture, 2004B) with data gaps filled using the STATSGO soil map coverage of California (U.S. Department of Agriculture, 1997). Land surface data specified by subregion for the Simulation application includes the curve number for each hydrologic soil group (A = 1, B = 2, C = 3 and D = 4), annual crops acreages, monthly precipitation and evapotranspiration rates, agricultural irrigation efficiency and irrigation return factor.

Figure 7

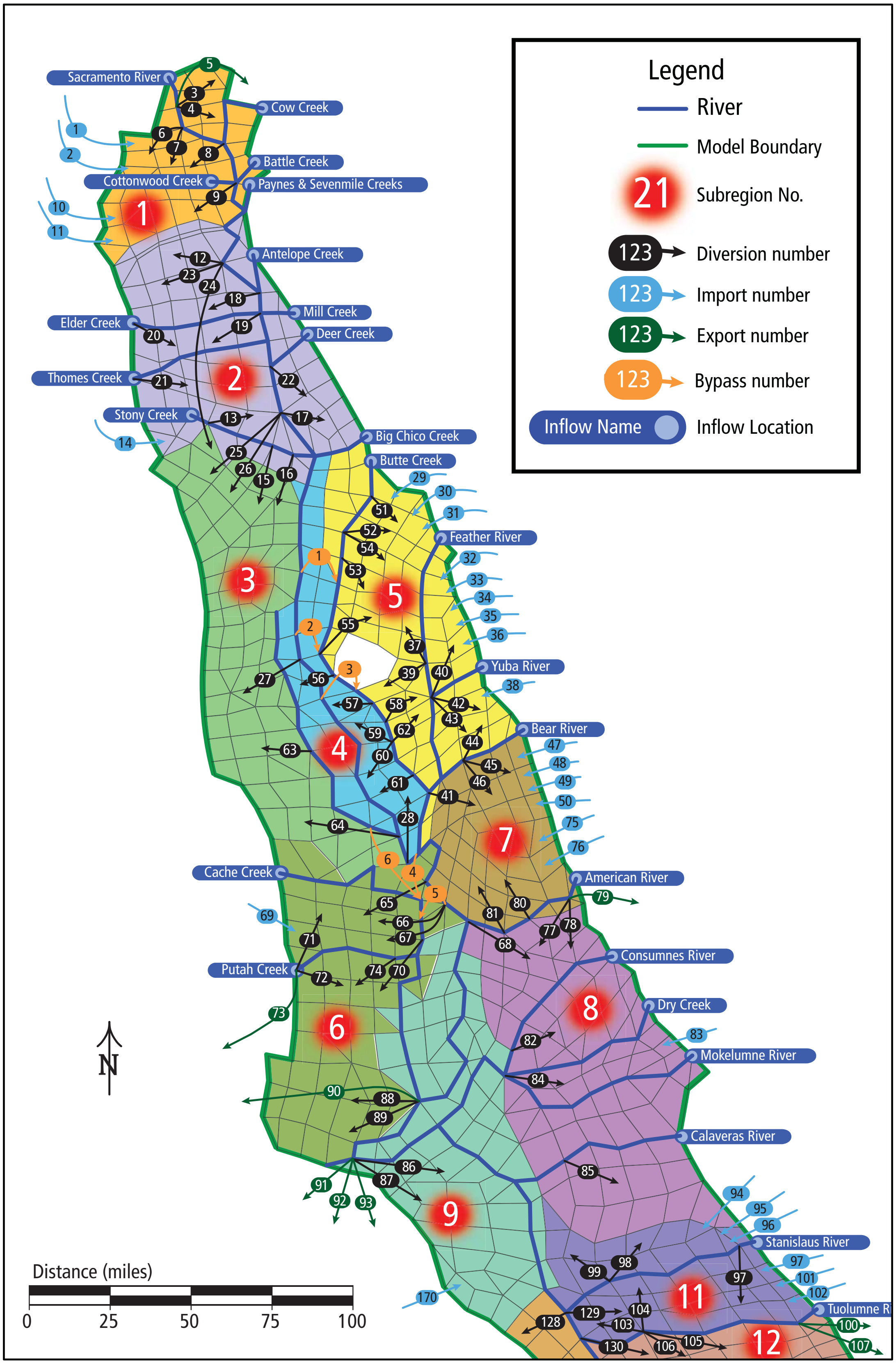


Surface-water flow network

The C2VSim surface-water flow network is composed of 449 river nodes delineating 75 stream reaches (figures 4 and 5), with 246 surface-water diversions, 12 bypasses and two lakes (figure 8). River nodes are generally numbered from the southern end of the model domain to the Delta, and then from the northern end of the model domain to the Delta, with some exceptions. All simulated river reaches discharge into either another river reach or a lake, with the exception of reach 74, in the Sacramento-San Joaquin Delta, which discharges outside the model boundary at the Carquinez Strait; this is the only simulated outflow for the model. Bypasses are used in the IWFM Simulation application to dynamically route water between river nodes, to simulate aquifer storage programs by routing water from a river node to direct recharge in specified model elements, and to route water from the Kern River to Buena Vista Lake. Each surface water diversion and bypass has a unique number, also shown in figure 8.

The C2VSim river network is based on the river network from the CVGSM model, with minor modifications; the following description of the CVGSM river network is from James M. Montgomery Consulting Engineers (1990B). For the CVGSM model, river cross section measurements were obtained for approximately

Figure 8a. C2VSim coarse grid with rim inflows, surface water diversions and surface water bypasses.



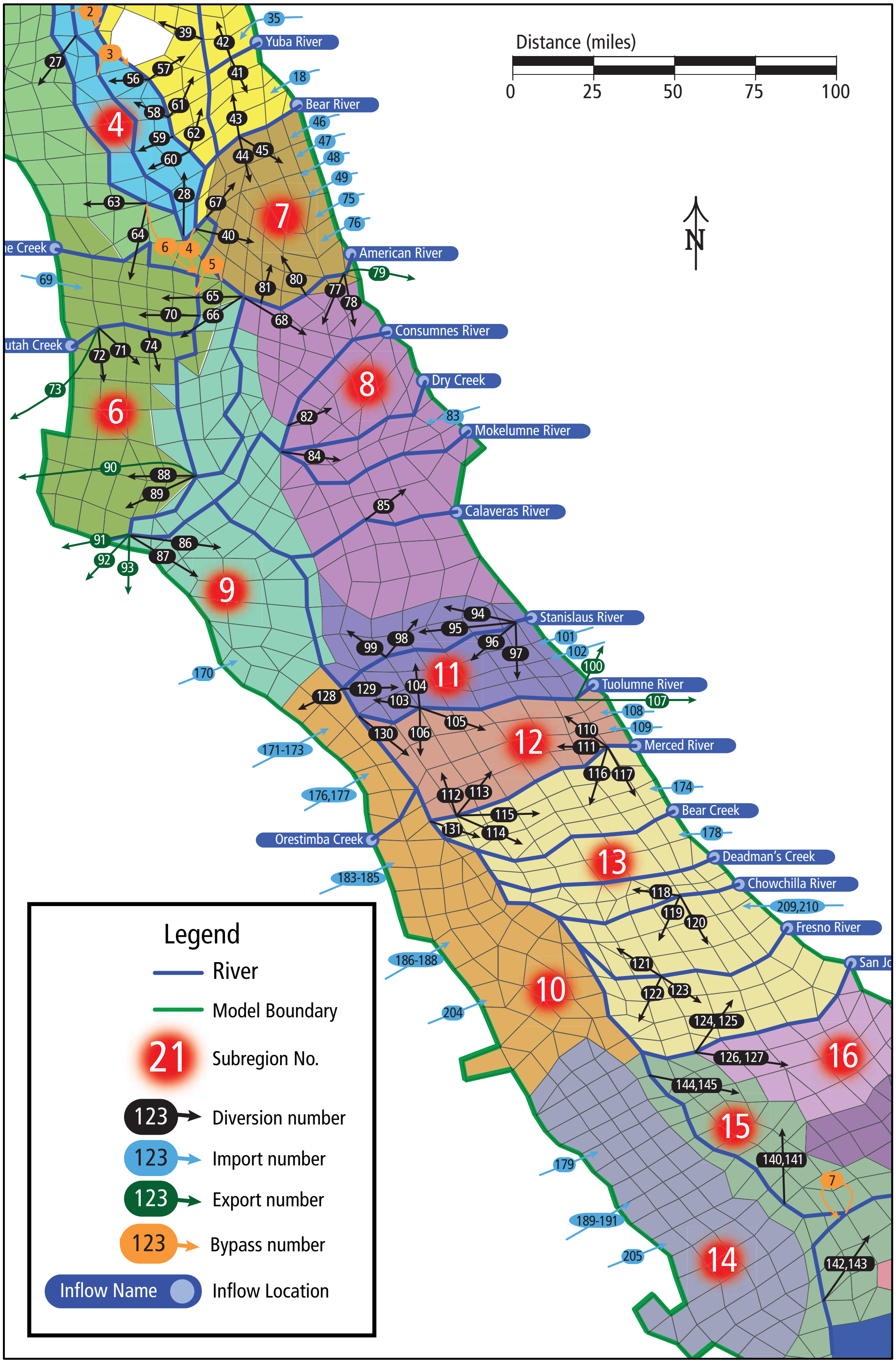


Figure 8b. C2VSim coarse grid with rim inflows, surface water diversions and surface water bypasses.

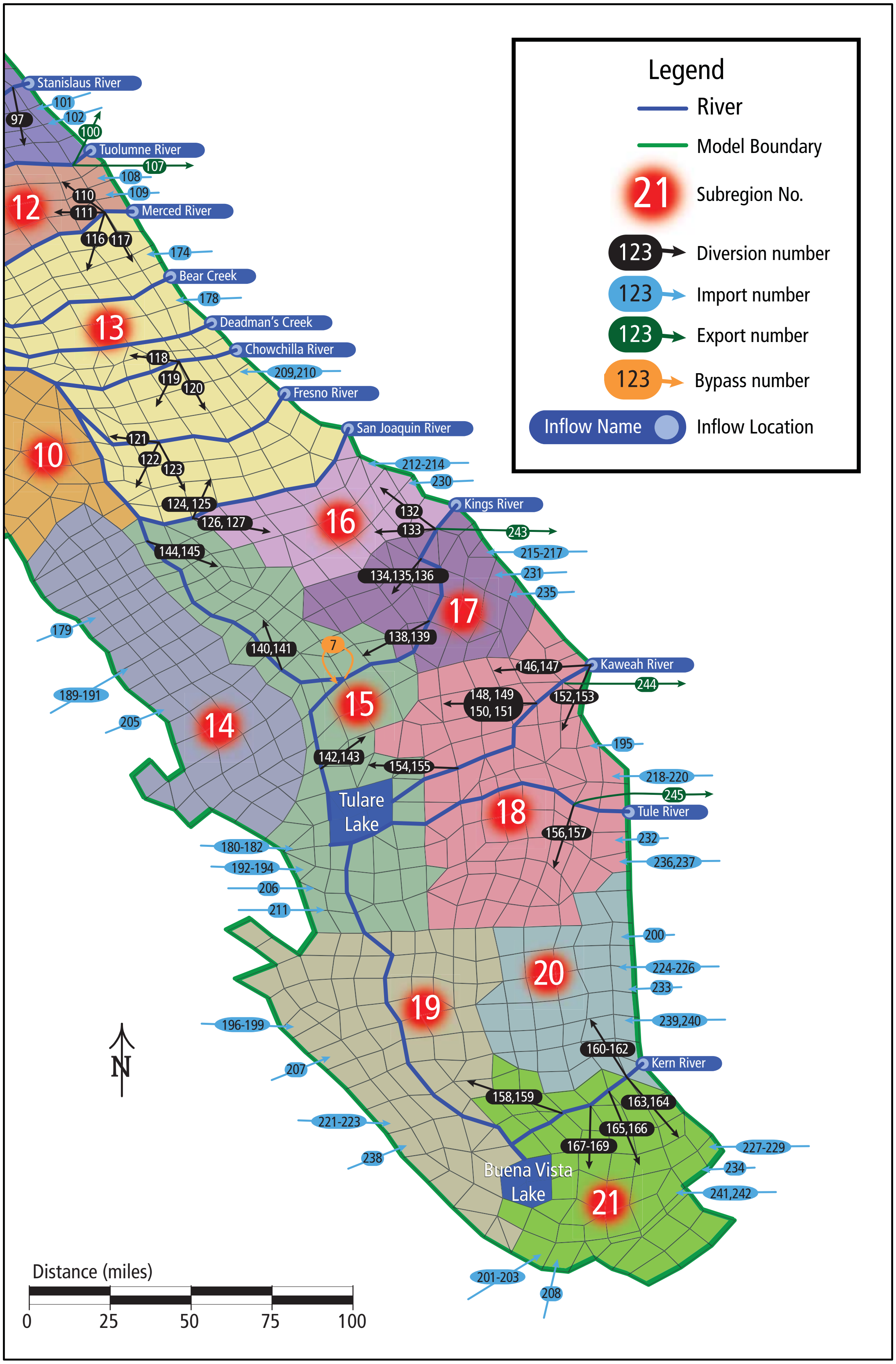


Figure 8c. C2VSim coarse grid with rim inflows, surface water diversions and surface water bypasses.

50 locations from the USGS and SWRCB. River depth-flow relationships were developed using the relationship:

Q = aDb and W = rDs,

where

Q is the discharge rate (cfs),

D is the depth of flow (ft), and

W is the wetted perimeter (ft).

The parameters a and b were obtained by plotting Q versus D on logarithmic paper. Application of Manning's equation then gave s = b – 5/3. Parameter r was obtained by using the maximum depth and maximum width of the river cross section. Depth-flow relationships for river nodes lacking cross sections were developed by either modifying a cross section for a similar river section (similar average annual flow, geographic location, etc.) or by using Manning's equation with a specified trapezoidal section and slopes (z = 1:4, sf = 0.005). The full description is available in James M. Montgomery Consulting Engineers (1990B).

The river network used in the C2VSim model was modified from that of the CVGSM model as follows. River bed elevations were adjusted so all river node altitudes are below the land surface altitude of the corresponding groundwater node (CH2M Hill, Inc., and S. S. Papadopulos and Associates, 2006). The depth-flow relationships for river nodes located in the Sacramento-San Joaquin Delta were adjusted to increase flow rates for specified depths, as these appeared to be too low in the CVGSM model. The Kern River flow path was modified, and river reaches were added to simulate the Kern River Flood Channel, outflow from the Suisun Marsh, and to extend the Sacramento-San Joaquin River in the Delta to the Carquinez Strait. Depth-flow relationships for river nodes added in the C2VSim model were estimated based on those at similar river nodes.

Lakes

Two lakes are simulated in the C2VSim model, Buena Vista Lake in Kern County and Tulare Lake in Tulare County (figure 8). Buena Vista Lake was used as a water storage reservoir until the construction of Lake Isabella was completed in 1954, then was converted to farm land. Kern County built Lake Webb and Lake Evans as part of the Buena Vista Aquatic Recreation Area on a portion of the old lake bed in 1973. Tulare Lake has generally been dry since 1899 with occasional flooding during periods of high river discharges and occasional operation of portions of the historic lake bed as agricultural reservoirs; agricultural crops are grown on most of the former lake bed. The two lakes were included in the CVGSM model and are therefore incorporated into the C2VSim model. The presence of these two lakes limits the accuracy of simulation results in these areas because they are simulated as water-containing lakes with static boundaries, but the flooded area has historically varied.

Buena Vista Lake is comprised of four elements, and receives inflow from the Kern River during extreme flood events, and discharges to the Kern River Flood Channel. The lake bed was used as a reservoir prior to the construction of Lake Isabella in 1954, and currently is largely dry. In rare instances when extreme flood events cause the historic lake bed to be flooded, the water is quickly pumped out and either exported by reoperating canals, used to irrigate crops, or diverted to recharge basins.

Tulare Lake is comprised of six model elements, and receives inflow from the Tule, Kaweah and South Fork of the Kings rivers and the Kern River Flood Channel. When the level of Tulare Lake rises above 286 ft, the lake discharges northward through the South Fork of the Kings River, James Bypass, Fresno Slough and the Mendota Pool to the San Joaquin River. The water level in Tulare Lake has not risen to 286 ft since the 1880s and the lakebed has generally been dry since 1899. Currently Kings River flows are controlled by Pine Flat Dam and two weirs which control flows at the Kings River bifurcation, Kaweah River flows are controlled by Temperance Flat Dam, Tule River Flows by Success Dam, and Kern River flows by Isabella Dam. Most of the flow from these rivers is now used to meet agricultural and urban water demands or is recharged through aquifer storage programs. In rare instances when extreme flood events cause the historic Tulare Lake bed to be flooded, the water is quickly pumped out and is either used to irrigate crops, or diverted to recharge basins.

Small-stream watersheds

Two hundred ten small-stream watersheds were delineated for the C2VSim model (figure 6) using the California Interagency Watershed Map of 1999 (CalWater 2.2.1, http://www.ca.nrcs.usda.gov/features/calwater/). The discharge point of each watershed was associated with an adjacent boundary groundwater node from the C2VSim grid. Where a small-stream watershed was associated with more than one boundary groundwater node, the watershed was subdivided using the USGS topographic map of the State of California to apportion flows between the groundwater nodes. The locations of stream arcs carrying small-stream watershed discharges from each simulated watershed were estimated using the USGS topographic map of the State of California. Soil hydrologic parameters for the small-stream watersheds were determined using SSURGO coverages for California's Central Valley (U.S. Department of Agriculture, 2004b).

Subsurface tile drains

In C2VSim, tile drains are specified at 11 nodes (figure 9), representing tile drains in Grasslands Drainers Area north of Westlands Water District (WWD), on the western side of the central San Joaquin Valley. Tile drains for 11 additional nodes representing the regional collector drain system in WWD are included in the tile drain file but are not activated, as these drains only operated between 1980 and 1984 and the current version of IWFM does not allow drain conductances to be simulated as a time series. All Grasslands Drainers Area drain flow discharges to stream node 114, under the assumption that flows are carried by the San Luis Drain, which is not explicitly simulated.

Historical data

Historical data for the C2VSim model includes surface water, land-surface process, and operational data. Surface water data include monthly inflow to rivers, and diversion and bypass flow values (including surface water imports and exports). Land-surface process data include annual land use distributions, monthly urban demands, precipitation rates, small- stream watershed inflows, and evapotranspiration rates. Operational data include irrigation efficiencies and the allocation of surface water diversions and groundwater pumping between agricultural and urban uses.

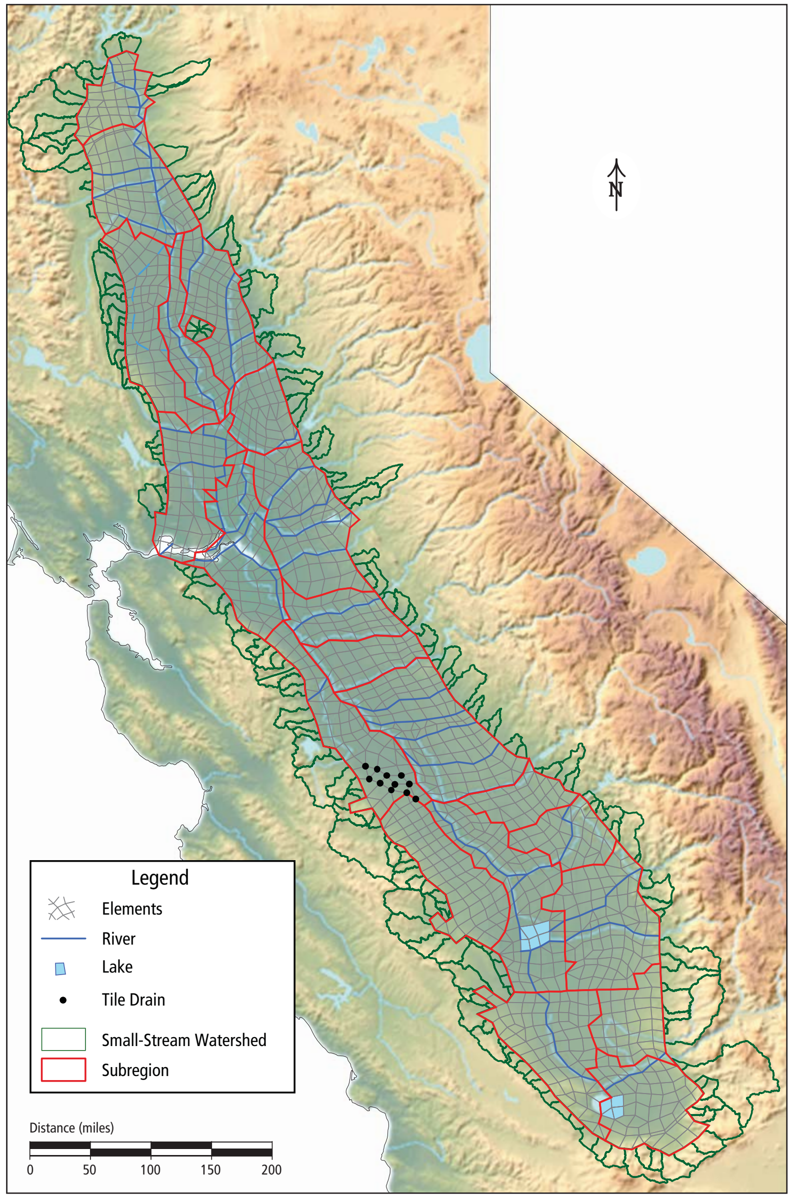
Surface Water

Surface water data includes boundary inflows, diversions and bypasses.

Surface-water boundary flows

Surface-water boundary inflows are specified at 41 locations (figure 8). Thirty-six represent inflows from major watersheds to the rivers (and streams) that are explicitly represented in the model. These rivers have gaged flows and are generally dammed. Historical monthly river inflow values were developed by DWR staff. Sources of river inflow data are listed in the companion report *Historical Rim Inflows, Surface Diversions and Bypass Flows*.

Figure 9. C2VSim coarse grid with the drain locations.



Surface-water diversions

Surface water supplies for agricultural and urban use are supplied by a complex water delivery system that includes natural in-stream flows, regulated releases into rivers, and regulated deliveries through canals. Historical monthly surface water diversions and imports for 246 locations (figure 8) were developed by DWR staff. Diversion and import data sources are listed in the companion report *Historical Rim Inflows, Surface Water Diversions and Bypass Flows*.

Surface-water bypasses

The C2VSim model has twelve bypasses (figure 8). Six bypasses simulate weir flows to flood basins located in the Sacramento Valley. The remaining six bypasses are located south of the Delta. One simulates flow through the Kings River bifurcation, four simulate stream-flow recharge on the distal part of river fans in the Tulare Basin, and one simulates flow from the Kern River to Buena Vista Lake. Flow rates for seven of the bypasses are specified as time series, and the flow rates for four are specified with rating tables. Historical monthly bypass flow rates were developed by DWR staff. Sources of bypass data are listed in the companion report *Historical Rim Inflows, Surface Water Diversions and Bypass Flows*.

The first six bypasses are located in the Sacramento Valley and are simulated using historical flow data. Bypasses 1 through 5 simulate the diversion of Sacramento River flows to the Sutter and Yolo Bypasses. The Moulton Weir, Colusa Weir and Tisdale Weir spill to the Sutter Bypass. The Fremont Weir and Sacramento Weir spill to the Yolo Bypass. Bypass 6 simulates Knights Landing Ridge Cut flows from the Colusa Basin Drain to the Yolo Bypass.

Bypass 7 simulates the Kings River Bifurcation at Army Weir and Island Weir, where flows are divided between the north and south forks of the Kings River. The river naturally flows to the North Fork Kings River, which flows northward through Fresno Slough, the James Bypass, and the Mendota Pool, to eventually discharge into the San Joaquin River. Flows are diverted into the South Fork Kings River for conveyance to diversions; this fork of the river terminates in Tulare Lake. The bypass is simulated using a historical record.

Bypasses 8 through 10 use rating tables to simulate aquifer storage programs in the distal portion of the Kaweah River, Tule River, and Kern River Flood Channel. Flows reaching the end of these channels are diverted to aquifer recharge under the assumption that (a) no flow reaches Tulare Lake, (b) river flow is actively managed to divert flows in excess of diversion requirements to groundwater recharge, and (c) any water reaching Tulare Lake is pumped out and used for irrigation or recharged. At the terminal nodes of river reaches ending at Tulare Lake, the IWFM bypass functionality is used to assign all available flow to recoverable losses (recharge) and therefore directly apply it as groundwater recharge to specified model elements. Bypass 11 uses a rating table to simulate aquifer storage progarms on the South Fork Kings River. There are no aquifer storage programs along this river reach, so this bypass is turned off.

Bypass 12 simulates flow from the Kern River to Buena Vista Lake. This can be simulated with a historical time series, but is provisionally set to zero for all time steps owing to a lack of data.

Land surface process data

Historical data for the land surface process includes annual land use and crop acreages, and monthly urban water demands, precipitation and evapotranspiration rates. Land use in the context of the C2VSim model describes the apportionment of each model element between agricultural crop acreage, urban land, native vegetation and riparian vegetation. Land use data for water years 1922-1980 were compiled from land use survey data collected by DWR and previously compiled for use in the DWR Consumptive Use model (James M. Montgomery Consulting Engineers, 1990B). Land use for the Consumptive Use model was compiled for Depletion Study Areas (DSAs, table 1), and was subsequently allocated to subregions using the areal land use distribution of the DWR land use surveys conducted between 1976 and 1980. Land use data for water years 1981-1992 were compiled by CH2M Hill (1996), land use data for water years 1993-2003 were compiled by DWR staff from detailed DWR land use surveys, and land use data for 2004-2009 were compiled by DWR staff from county agricultural commissioner reports.

The precipitation data file contains monthly precipitation for the period October 1921 through September 2009 for each model element and small-stream watershed. These precipitation rates were calculated as the area-weighted average from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) 2 km x 2 km monthly precipitation datasets (Oregon Climate Service, written communication, 2010). Monthly average evapotranspiration rates for each agricultural crop, each of the other three land use classes and each small watershed were compiled from DWR Bulletin 113-3 (DWR, 1975) and DWR Bulletin 113-4 (DWR, 1986).

Table 1. C2VSIM hydrologic regions, subregion numbers and corresponding Depletion

Study Area numbers, area, and number of model elements.

Hydrologic Region	Subregion	DSA	Area (ac)	Area (mi2)	Area (km2)	Elements
1	1	58	328,278	513	1,329	46
	2	10	698,014	1,091	2,825	84
	3	12	689,108	1,077	2,789	79
	4	15	351,576	549	1,423	46
	5	69	613,756	959	2,484	77
	6	65	657,863	1,028	2,662	64
	7	70	349,858	547	1,416	46
		totals	3,688,452	5,764	14,928	442
2	8	59	895,534	1,399	3,624	88
3	9	55	725,454	1,134	2,936	78
4	10	49A	668,072	1,044	2,704	70
	11	49B	412,543	645	1,670	44
	12	49C	340,336	532	1,377	33
	13	49D	1,037,638	1,621	4,199	117
		totals	2,458,589	3,842	9,950	264
5	14	60A	670,229	1,047	2,712	71
	15	60B	904,472	1,413	3,660	105
	16	60C	302,449	473	1,224	31
	17	60D	372,889	583	1,509	39
	18	60E	897,091	1,402	3,631	90
	19	60F	801,420	1,252	3,243	77
	20	60G	423,713	662	1,715	42
	21	60H	652,847	1,020	2,642	65
		totals	5,025,110	7,852	20,336	520
		Total	12,793,139	19,991	51,774	1,392

Operational data

Operational data, which is incorporated into the land surface process, includes the supply adjustment specification, irrigation efficiency, irrigation water re-use factors, urban water use specification, and pumping specification. For the C2VSim model, the supply adjustment specification is set to indicate that groundwater pumping rates will be adjusted to balance water supply and demand, and surface water diversions will not be adjusted. The irrigation fraction specifies that elemental groundwater pumping is directed to meet agricultural water demands, and pumping from specified wells is directed to meet urban water demands. Irrigation water re-use factors specify the amount of irrigation return flow that is assumed to be re-diverted within each subregion to meet irrigation demands.

Initial conditions, simulation period and time step

IWFM incorporates time-stamped data sets for model inputs, which allow C2VSim simulations to be conducted for the period from October 1921 through September 2009 with a monthly or daily time step, or from any starting date after October 1921 for which initial conditions are available. Initial conditions for October 1921 were hand contoured from available groundwater head data and ground surface altitudes. Initial conditions for October 1972 were developed for the first phase of model calibration by CH2M Hill, Inc. and S.S. Papadopoulos and Associates (2006). Initial lake elevations for Buena Vista Lake and Tulare Lake are assumed to be equal to the minimum land surface elevation for the model elements comprising each lake. Initial soil moisture values are listed for the root zone (by subregion), the unsaturated zone (for each element), and small stream watersheds (by watershed group) were derived by running the model for 60 monthly time steps with constant October 1921 input values.

C2VSim Calibration

The C2VSim model was calibrated in three phases using the PEST parameter estimation programs (Doherty, 2004). In the first phase, computer programs were created to link the IWFM application with the PEST parameter estimation program (CH2M Hill and S.S. Papadopoulos and Associates, 2005), and PEST was used to calibrate regional-scale aquifer parameter values at 139 pilot points (CH2M Hill and S.S. Papadopoulos and Associates, 2006). Simulated head and flow values were matched to semi-annual groundwater head observations at 121 locations and monthly surface water flow observations at 9 locations from October 1975 to September 1999, and average monthly stream-aquifer interaction values at 65 locations. During this calibration phase, the C2VSim model underwent several modifications, including refinement of the aquifer stratigraphy and stream bed elevations.

In the second calibration phase, PEST was used to calibrate local-scale aquifer parameter values at 394 pilot points. The calibration data set included 56,947 monthly groundwater head observations at 1,387 wells (including 3,016 vertical head differences at 121 locations), 5,636 monthly stream flow observations at 26 locations from October 1975 to September 1999, and average monthly stream-groundwater flow values along 33 stream reaches. Several minor modifications were subsequently made to the model framework, the input data sets were thoroughly reviewed, and the surface water inflow and surface water data sets were completely reconstructed through September 2009.

In the third calibration phase, PEST was used to calibrate aquifer parameter values at each model node using the same observation data set as the second calibration phase, augmented with 3,700 subsidence observations at 24 extensometers. The calibration was conducted using resources of the National Energy Research Scientific Computing Center (http://www.nersc.gov/), which is supported by the Office of Science of the U.S. Department of Energy under contract DE-AC02-05CH11231.

Calibration Results

Five types of observations were used to calibrate the C2VSim model: groundwater heads, vertical groundwater head differences, river flows, average groundwater-surface water flows, and subsidence. Model performance was measured as the root mean square error (RMSE) and mean error (ME) for each observation type.

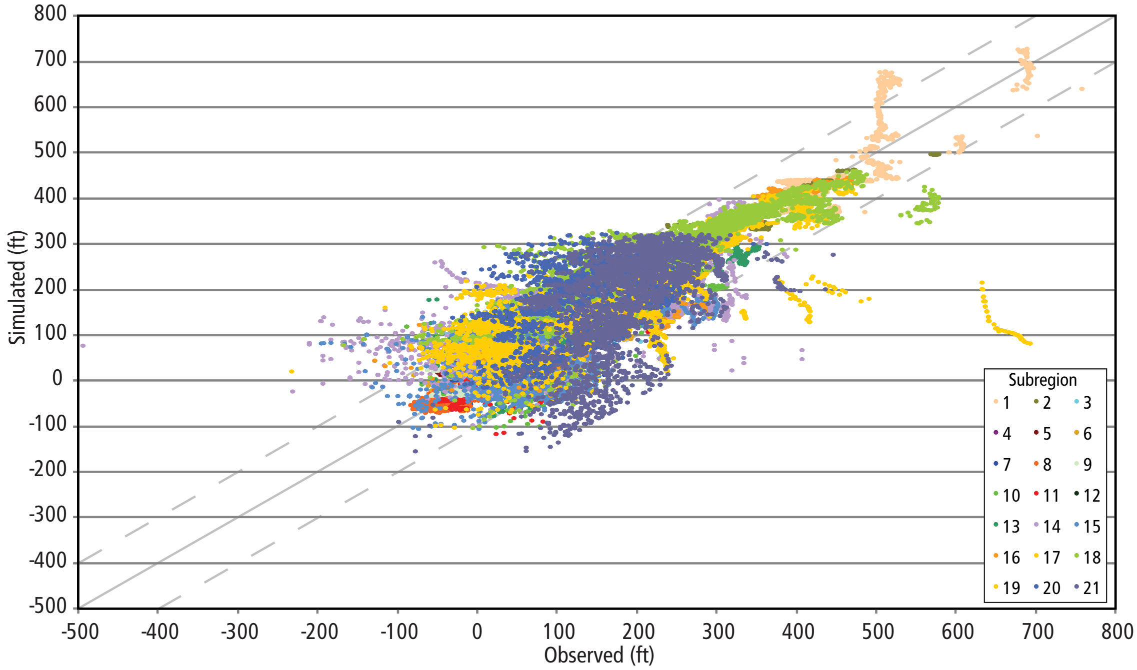
Table 2. Model performance measures for aquifer heads, water years 1975-2003.
[Feet]

Subregion	Wells	WL Obs	RMSE	Residual	RMSE/Range	Residual/Range
Sacramento Valley						
SR 1	24	1,645	42.1	5.8	0.109	0.015
SR 2	45	3,665	25.0	4.6	0.052	0.009
SR 3	54	4,761	19.1	-3.5	0.078	-0.014
SR 4	17	1,087	8.4	4.1	0.062	0.030
SR 5	61	4,867	17.7	5.1	0.081	0.024
SR 6	53	4,013	26.8	1.9	0.079	0.006
SR 7	31	1,545	22.0	1.9	0.087	0.007
HR 1	285	21,592	23.8	2.3	0.028	0.003
Eastside Streams						
SR 8	62	4,209	16.0	-0.6	0.058	-0.002
Sacramento-San Joaquin Delta						
SR 9	42	1,522	19.8	7.0	0.135	0.048
San Joaquin Basin						
SR 10	101	3,567	37.8	8.2	0.094	0.021
SR 11	37	2,163	22.3	10.6	0.085	0.040
SR 12	24	835	25.7	-13.0	0.111	-0.056
SR 13	144	5,484	36.3	-14.3	0.082	-0.032
HR 4	306	12,049	34.0	-3.1	0.077	-0.007
Tulare Basin						
SR 14	164	3,416	87.0	20.3	0.096	0.022
SR 15	135	4,467	59.0	11.8	0.119	0.024
SR 16	40	1,613	36.0	6.2	0.059	0.010
SR 17	43	1,793	42.4	14.5	0.060	0.021
SR 18	107	4,817	64.2	-34.7	0.086	-0.047
SR 19	69	2,680	109.4	5.4	0.141	0.007
SR 20	39	1,517	87.9	-50.0	0.219	-0.125
SR 21	86	3,306	94.1	13.6	0.153	0.022
HR 5	683	23,609	76.9	-1.1	0.065	-0.001
ALL	1378	62,981	51.6	-0.1	0.041	-0.0001

ME = Mean error
RMSE = Root mean squared error
SR = Subregion
HR = Hydrologic region

Model performance measures for groundwater heads are presented in table 2 and figure 10. The difference between simulated and observed heads is smallest in the Sacramento Valley and greatest in the Tulare Basin. The performance measures RMSE/range and ME/range are small, indicating good model performance. Simulated groundwater heads over time are greatly affected by the flows into and out of the aquifer, mainly recharge and pumping. The IWFM application averages these flow terms over each model subregion, limiting the ability of the model to match local heads.

Figure 10. Simulated and observed groundwater heads for the model calibration period, water years 1975-2003 (62,981 observations).



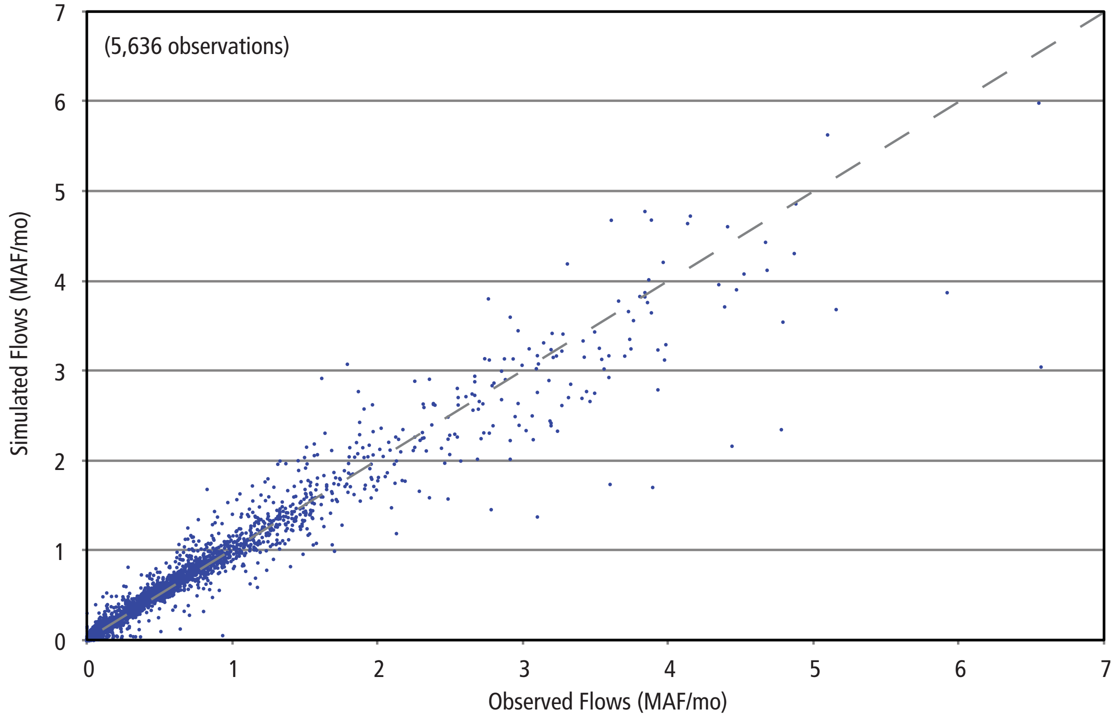
Model performance for surface water flows is presented in table 3 and figure 11. Simulated and observed flows are very close for low and moderate flows, and show some divergence for high flows. The Central Valley surface water flow system is dynamic, and changed significantly between 1921 and 2009. In 1921, there were few large reservoirs regulating winter flows into the Central Valley, and significant over-bank flow occurred during high flow events. In the 1940's, a flood control system incorporating levees and bypasses was built, reducing over-bank flows. C2VSim has a static representation of the surface water flow system, which cannot mirror the changes that have occurred between 1921 and 2009. The C2VSim model simulates the post-1950 configuration of the Central Valley flow system. Owing to the static surface water configuration, the basic C2VSim model may not accurately simulate surface water flows during extreme flood events.

Table 3. Model performance measures for river flows, water years 1975-2003.

Gage	Obs	RMSE (TAF)	ME (TAF)	RMSE Range	ME Range	Nash-Sutcliffe
Sacramento River Basin						
Sacramento River at Red Bluff	337	191.1	-48.9	0.050	-0.013	0.88
Sacramento River at Ord's Ferry	337	179.9	-8.7	0.030	-0.001	0.91
Sacramento River at Knights Landing	337	116.8	-12.3	0.032	-0.003	0.92
Feather River at Yuba City	109	204.4	-47.3	0.047	-0.011	0.89
Yuba River before Marysvills	337	186.1	-38.1	0.039	-0.008	0.91
Feather River at Olivehurst	61	132.3	-16.1	0.033	-0.004	0.97
Sacramento River at Verona	337	244.5	25.1	0.037	0.004	0.85
Bear River at Wheatland	337	83.1	-37.1	0.019	-0.008	0.98
American River at Fair Oaks	337	75.3	-8.1	0.020	-0.002	0.99
Sacramento River at Freeport	337	137.6	6.6	0.029	0.001	0.91
Cache Creek near Woodland	337	170.6	22.1	0.036	0.005	0.95
Sacramento River Basin	3,203	163.6	-12.4	0.025	-0.002	
Eastside Streams Region						
Dry Creek near Galt	241	117.3	4.3	0.023	0.001	0.97
Cosumnes River at McConnell	86	61.8	-33.3	0.019	-0.010	0.99
Mokelumne RIver at Woodbridge	313	115.2	-56.2	0.023	-0.011	0.95
Eastside Streams Region	640	110.4	-30.3	0.021	-0.006	
San Joaquin River Basin						
San Joaquin River near Mendota	45	116.5	-41.1	0.042	-0.015	0.96
Merced River at Stevinson	265	92.5	16.0	0.020	0.003	0.99
Tuolumne River at Merced	337	162.6	-23.7	0.033	-0.005	0.94
San Joaquin River at Crows Landing	96	89.9	-50.5	0.105	-0.059	0.83
Orestimba Creek near Crows Landing	138	28.7	-5.5	0.012	-0.002	1.00
Stanislaus River at Ripon	238	84.5	21.5	0.013	0.003	0.99
San Joaquin River at Newman	337	143.4	-16.7	0.037	-0.004	0.94
San Joaquin River at Vernalis	337	104.8	-13.9	0.024	-0.003	0.95
San Joaquin River Basin	1,793	118.1	-9.2	0.018	-0.001	
Central Valley						
ALL	5,636	145.0	-13.4	0.022	-0.002	

ME = Mean error
RMSE = Root mean squared error
Qmax = maximum recorded monthly flow

Figure 11. Simulated and observed surface water flows for the model calibration period, water years 1975-2003 (3,176 observations).



Running C2VSim

The IWFM suite includes four programs (Pre-processor, Simulation, Budget and Z-Budget) which are executed from the command line. Full details on the IWFM programs can be found in the reports Integrated Water Flow Model (IWFM 3.0) Theoretical Manual (Dogrul 2012A), Integrated Water Flow Model (IWFM 3.0) User's Manual (Dogrul 2012B), and Z-Budget: Sub-domain Water Budgeting Post-Processor for IWFM, Theoretical Documentation and User's Manual (Dogrul 2012C), available on-line at http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM. A typical model run involves executing the Pre-processor, Simulation and Budget programs one time each in sequence, and then executing the Z-Budget program one or more times to produce budgets for different user-defined zonal configurations. Each program can accept the name of the corresponding main input file on the command line. The following example shows how the IWFM programs are executed for a C2VSim run.

```
> Pre-processor CVPreproc.in

> Simulation CVSim.in

> Budget CVBudget.in

> Zbudget ZBudget_All.in

> Zbudget ZBudget_HRs.in

> Zbudget ZBudget_SRs.in

> Zbudget ZBudget_Elem.in

> Zbudget ZBudget_Elem_L1.in

> Zbudget ZBudget_Elem_L3.in

> Zbudget ZBudget_Elem_L2.in
```

The C2VSim Framework – The IWFM Pre-processor Program

The IWFM Pre-processor program compiles static model components, including spatial, stratigraphic and hydrologic data, checks for consistency among these components, and produces a binary file that is read by the Simulation program. The C2VSim model framework is defined by the Pre-processor input files. This static data includes the finite element grid (nodes, elements, and layer stratigraphy), the river network, lakes, individual wells, and elemental characteristics including soil properties and precipitation stations. Output units and required conversion factors are also specified in the main Pre-processor Input File. The information contained in the Pre-processor input files for C2VSim is described below. Much of the Pre-processor information was based on the CVGSM model (James M. Montgomery Consulting Engineers, 1990B).

Input Files

The main Pre-processor Input File lists all input files read by the Pre-processor program and all output files to be produced. Lines that begin with the 'C', 'c' or '*' character in the first character position are treated as comments and are ignored by the Pre-processor program. The portion of any line after a forward slash character '/' is also treated as a comment.

Pre-processor Main Input File

The Pre-processor Main Input File CVpreproc.in contains a list of the files read by the Pre-processor, several control flags, and factors to convert internal length and area units to output units. The input files are listed in table 4. The first three non-comment lines of the Pre-processor Input File are title lines that are placed in the main Pre-processor output file for future reference.

The flag KOUT is set to 1 to print out detailed geometric and stratigraphic information for the model grid, or 0 otherwise. The flag KDEB is set to 2 to print messages to the screen during program execution, 1 to print out non-zero finite element stiffness matrix components, or 0 to print neither of these. C2VSim uses an internal length unit of one foot, and output lengths are specified as units of feet (UNITLTOU = FEET), so no length conversion is required (FACTLTOU = 1). Areas are printed out in units of acres (UNITAROU = ACRES), so an area conversion is required (FACTAROU = 0.000022957).

Table 4. Pre-processor files.

No.	File Name	Type	File Contents
4	CVpreout.bin	Binary	Output file (binary format)
5	CVpre.in	Text	Main input file
7	CVelement.dat	Text	Element and node specification
8	CVnode.dat	Text	Nodal x-y coordinates
9	CVstrat.dat	Text	Aquifer stratigraphy
10	Cvrivers.dat	Text	River network configuration
11	CVlake.dat	Text	Lake configuration
12	Cvwells.dat	Text	Well locations and characteristics
13	CVcharac.dat	Text	Element hydrologic characteristics

Nodal Coordinates File

The Pre-processor Nodal Coordinates File CVnodes.dat contains the number of nodes, a factor to convert nodal coordinate length units to simulation length units, and an ordered list of nodes and their x-y coordinates. IWFM will accept any coordinate system as long as the appropriate conversion factor is given. C2VSim model grid has 1393 nodes (ND = 1393). Nodal coordinates are specified in UTM Zone 10 NAD 1983 in units of meters, with northing as x-coordinate and easting as y-coordinate. These are converted to the internal units of feet (FACT = 3.2808). Addendum A.1 contains a list of model nodes and their x-y coordinates. The model grid with node numbers is displayed in figure 2.

Element Configuration

The Pre-processor Element Configuration File CVelement.dat contains the elemental configuration for the C2VSim model grid. There are 1392 elements in the model domain (NE = 1392). Each element is formed from either three or four nodes, with element interfaces described by straight lines connecting the nodes. Four nodes are listed for each element, with triangular elements having node "0" for the fourth node. The nodes or each element are listed in the counter-clockwise direction. Addendum A.2 contains a list of model elements and their corresponding nodes. The model grid with element numbers is displayed in figure 3.

Stratigraphy

The Pre-processor Stratigraphy File CVstrat.dat details the structural composition and distribution of simulated aquifer layers. Each modeled aquifer layer is composed of two components, an aquiclude or aquitard of variable thickness overlying an aquifer layer of variable thickness. In IWFM's quasi-three-dimensional finite element formulation, vertical groundwater flow occurs in the aquiclude or aquitard and the aquifer, and horizontal flow occurs only between adjacent nodes in the aquifer. The stratigraphy file lists the number of aquifer layers (NL = 3), and a factor to convert layer thickness given in feet to simulation length units (FACT = 1 as C2VSim uses length units of feet). The stratigraphy information is listed for each node, starting with the land surface altitude, followed by the aquiclude and aquifer thicknesses of each model layer, in sequential order from top to bottom. The C2VSim model has no aquiclude above the top layer (1) or above the bottom layer (3) so these aquiclude thicknesses are set to zero. The aquiclude above the middle aquifer layer (2) represents the Corcoran Clay unit of the Tulare Formation, where it is present. Addendum A.1 contains the top and bottom elevation for each layer associated with for each model node. Figures 12A-Q shows the model layer elevations for 11 east-west cross sections and six north-south cross sections through the Central Valley aquifer.

Figure 12A. C2VSim cross section A-A′

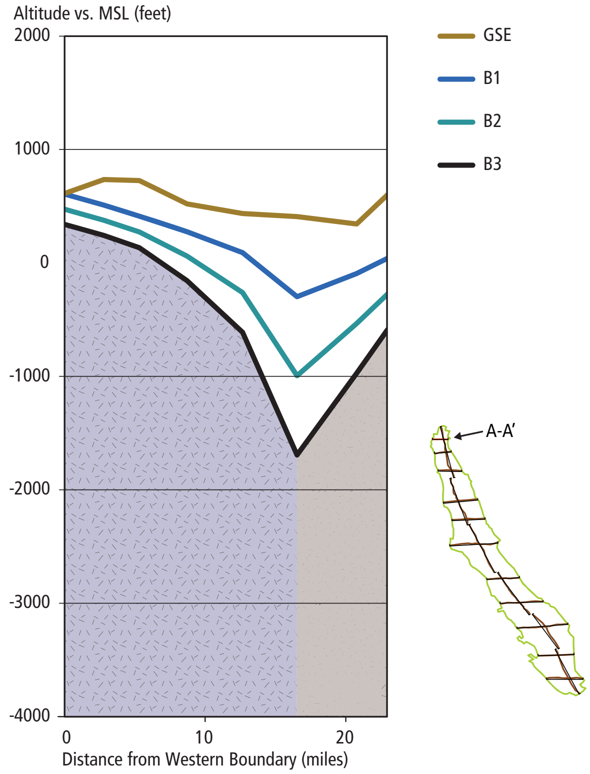


Figure 12B. C2VSim cross section B-B′

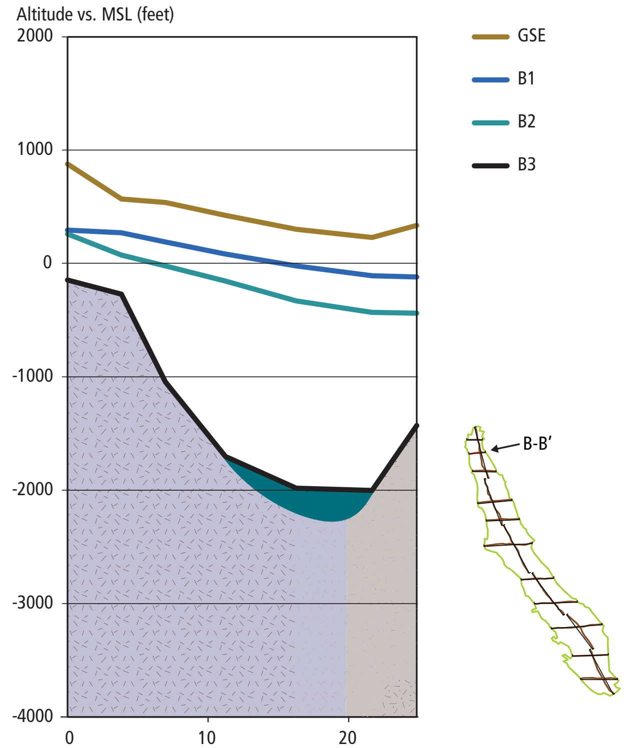


Figure 12C. C2VSim cross section C-C′

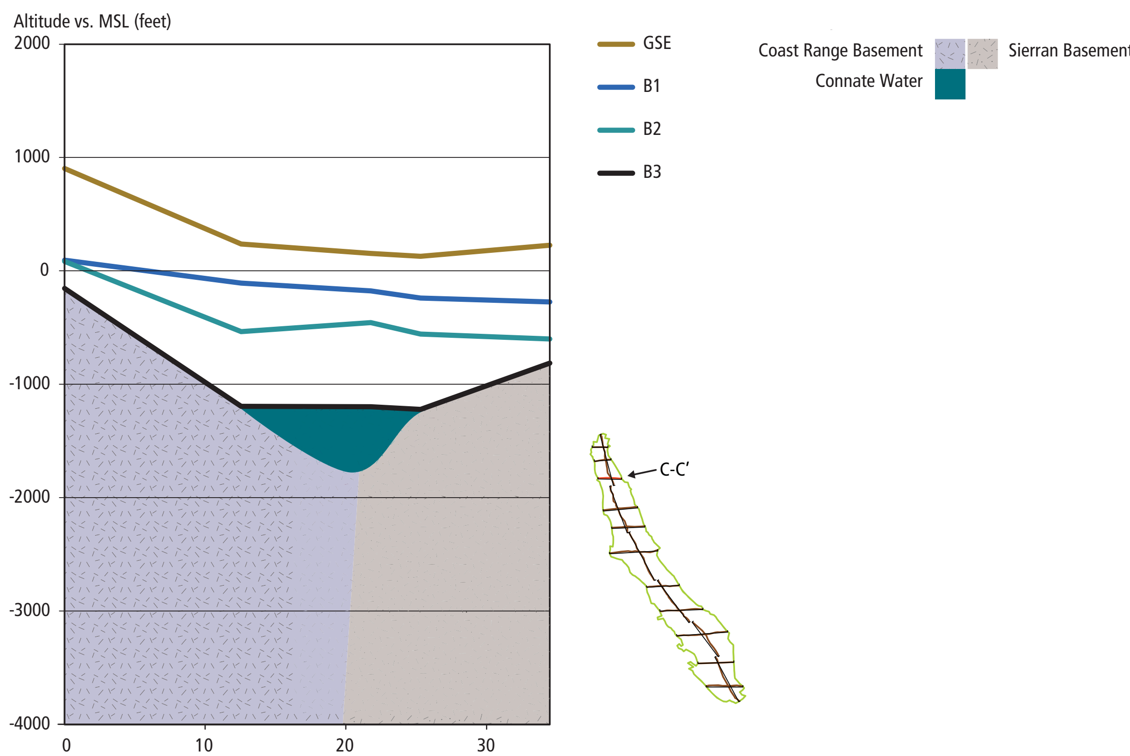


Figure 12D. C2VSim cross section D-D'

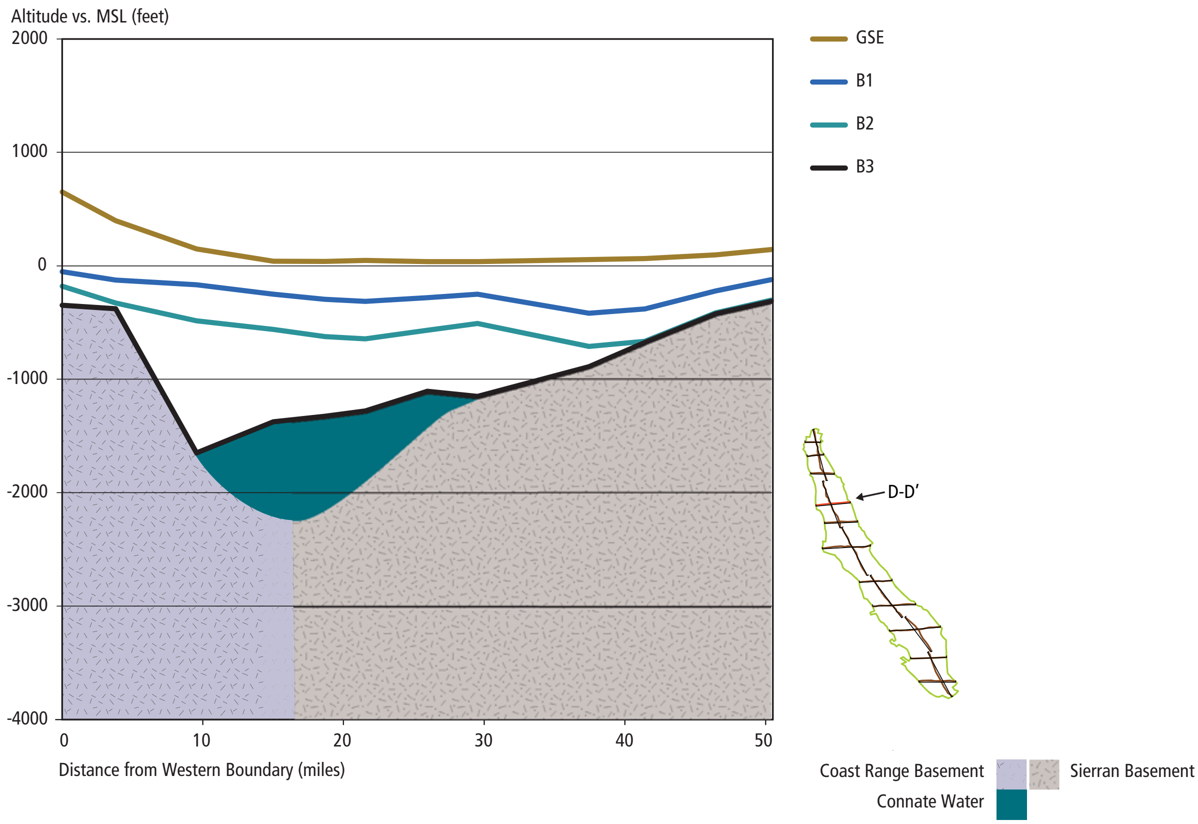


Figure 12E. C2VSim cross section E-E'

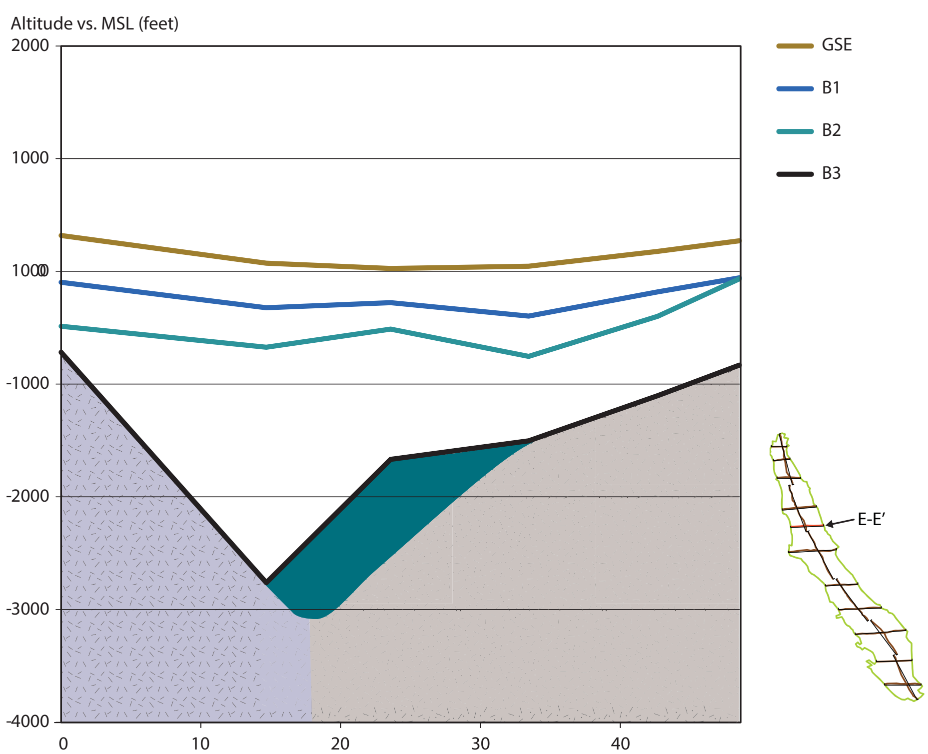


Figure 12F. C2VSim cross section F-F'

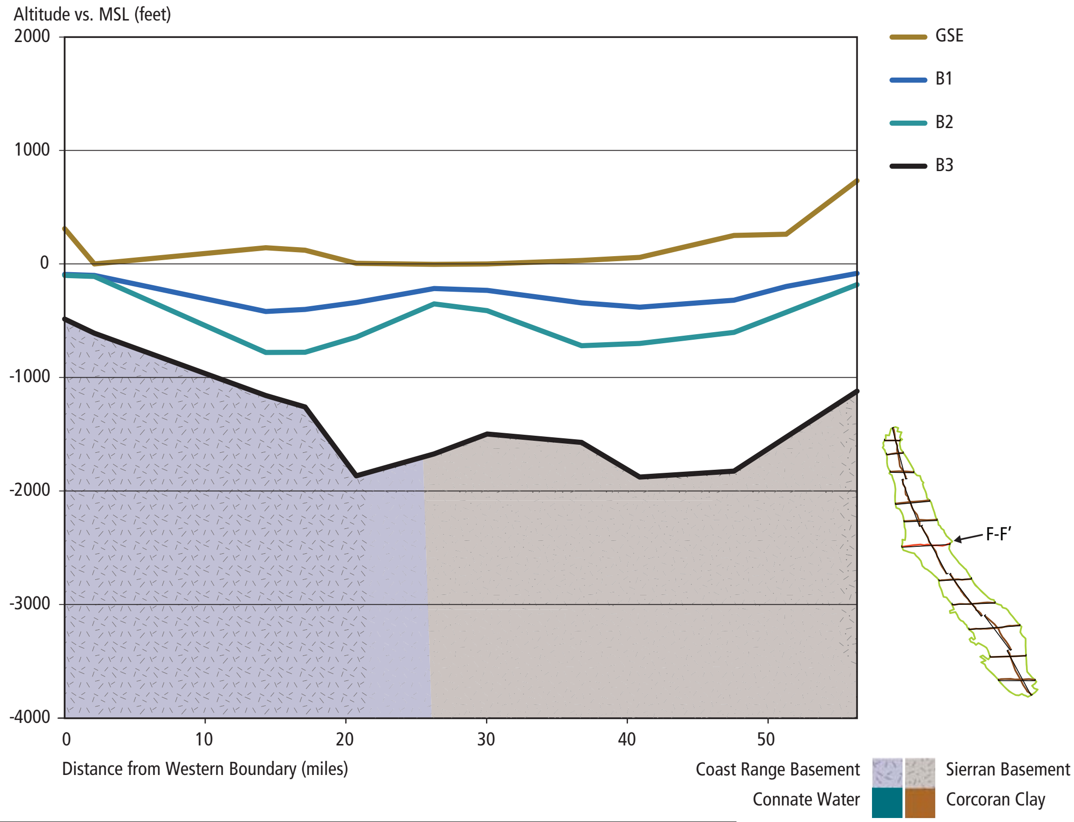


Figure 12G. C2VSim cross section G-G'

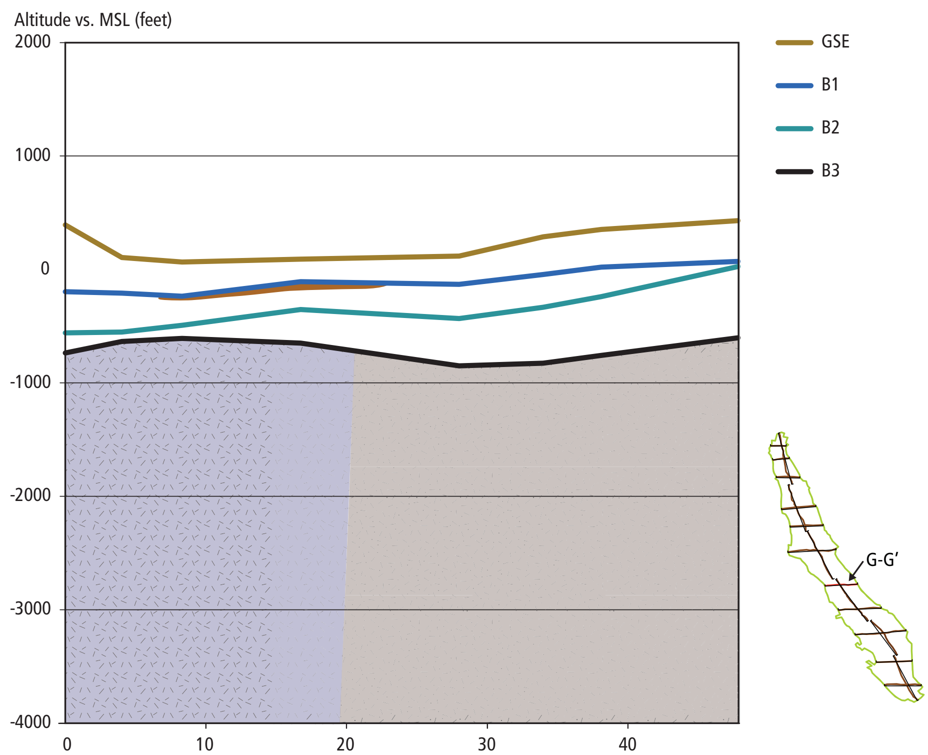


Figure 12H. C2VSim cross section H-H'

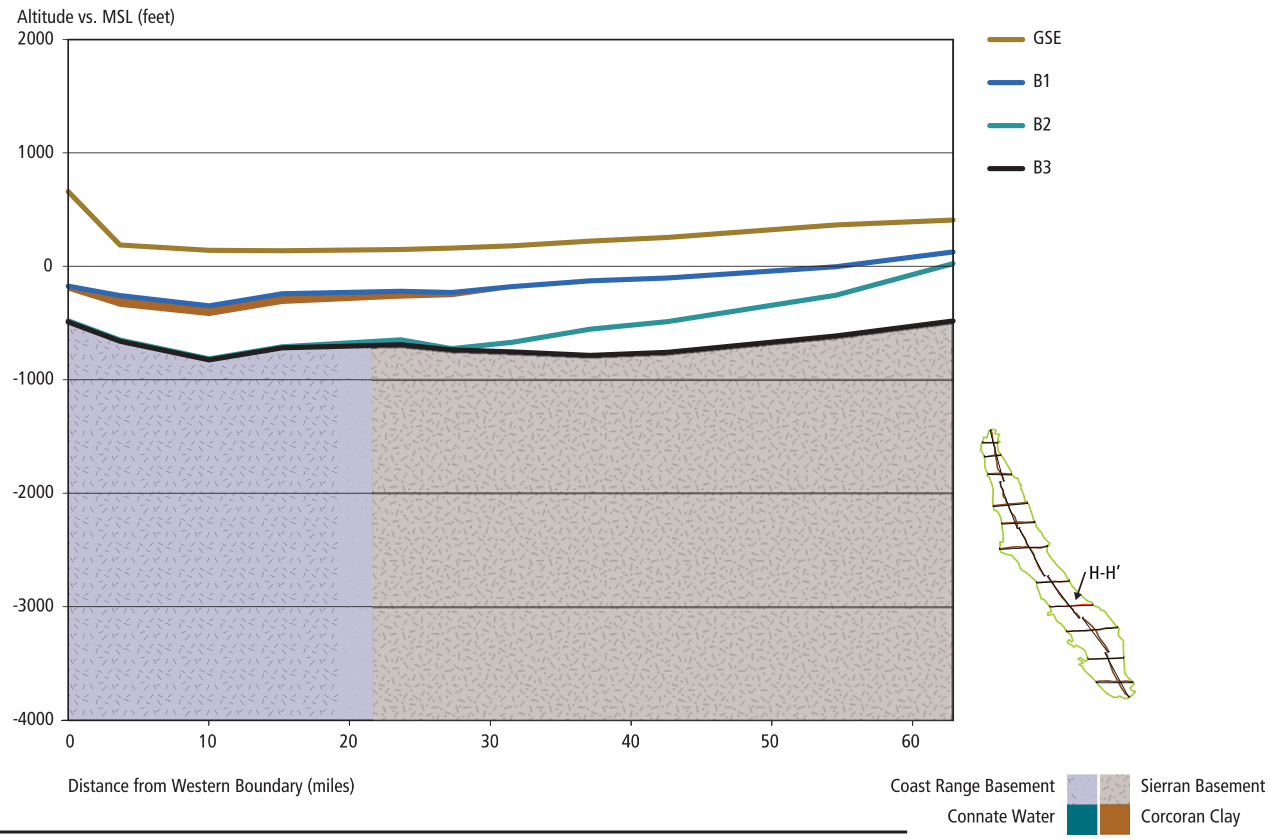


Figure 12I. C2VSim cross section I-I'

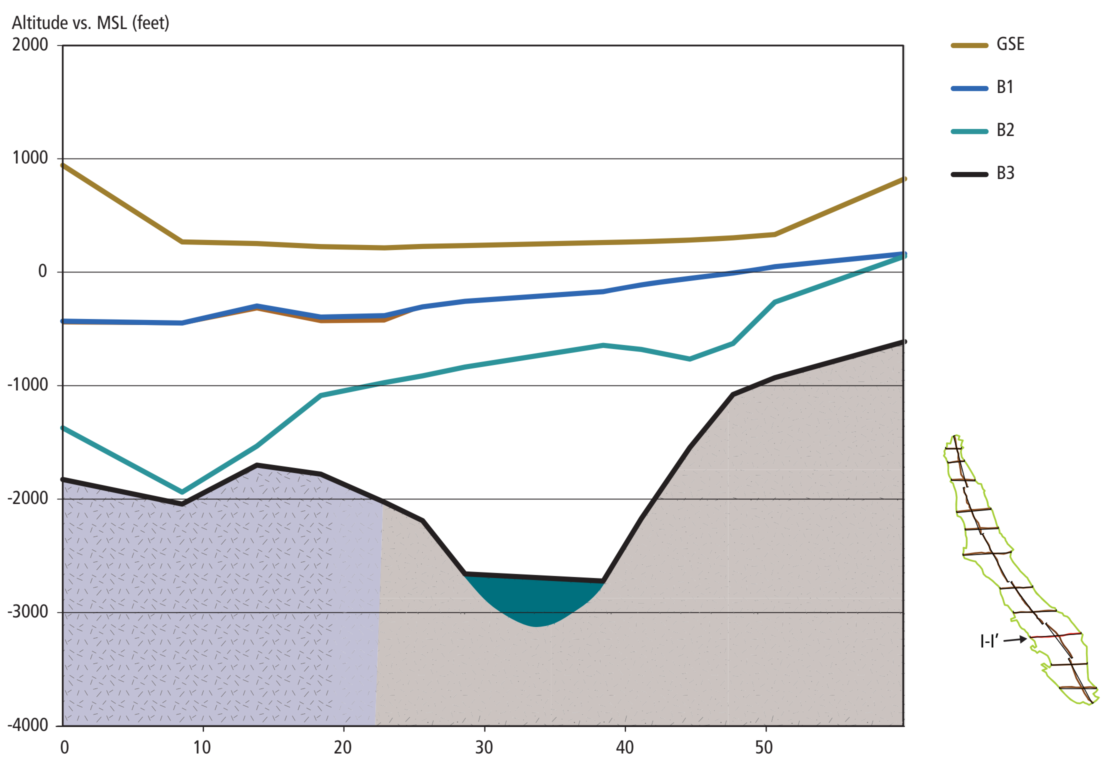


Figure 12J. C2VSim cross section J-J'

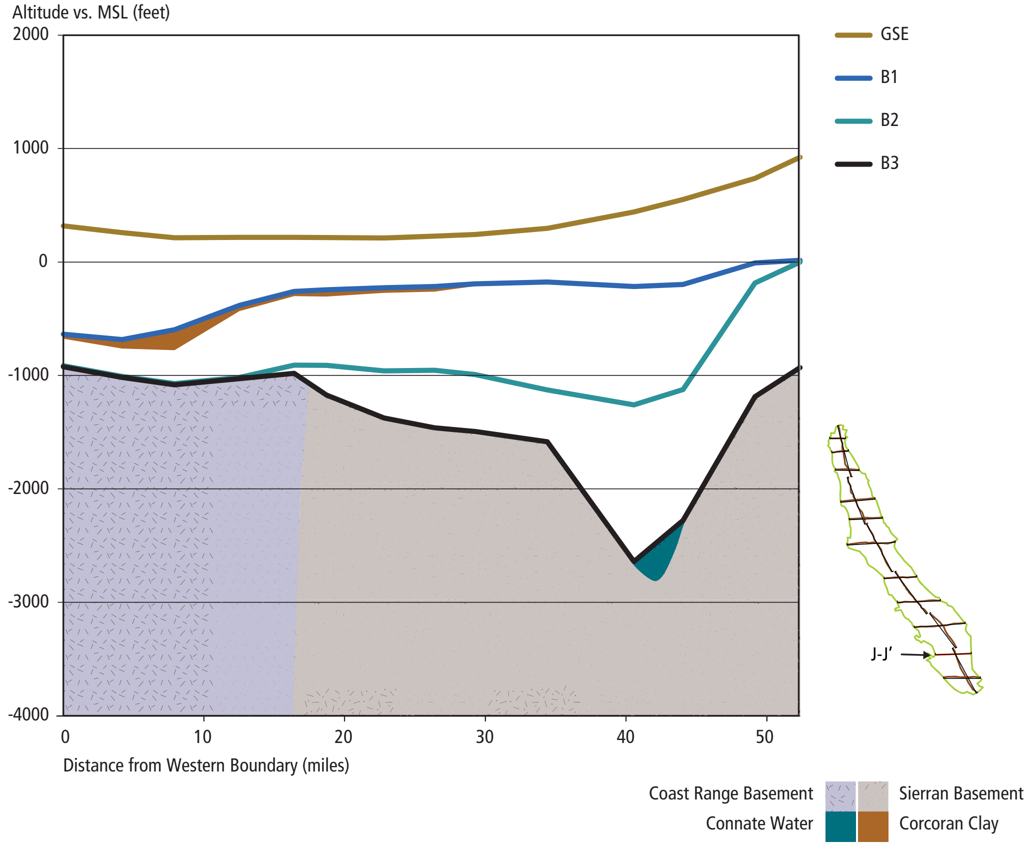


Figure 12K. C2VSim cross section K-K'

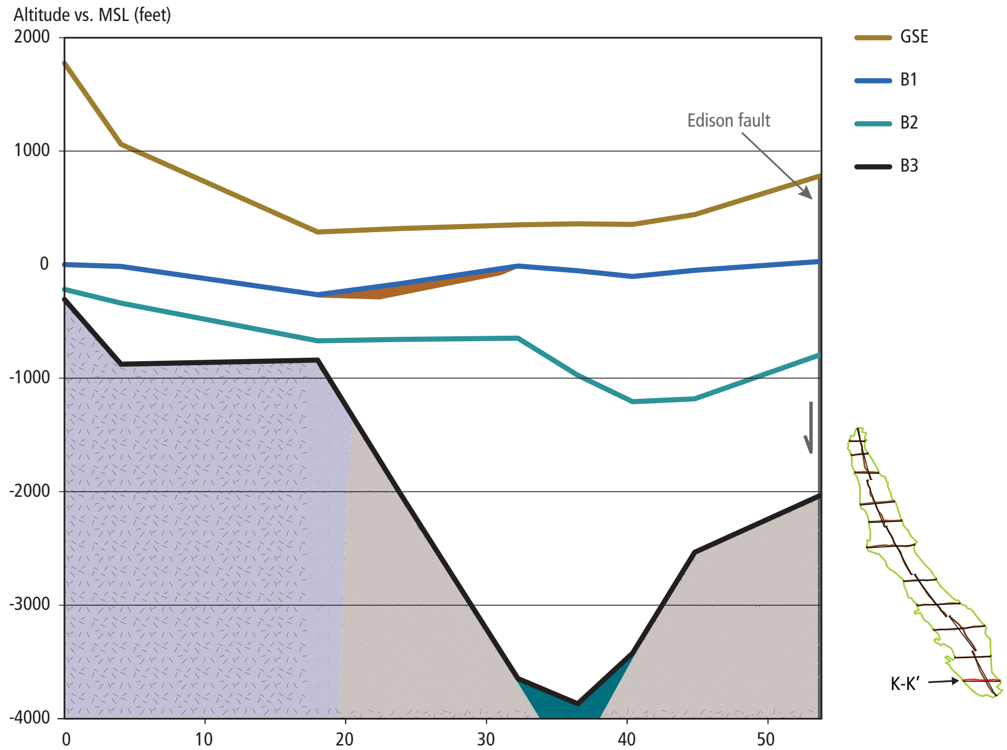


Figure 12L. C2VSim cross section L-L'

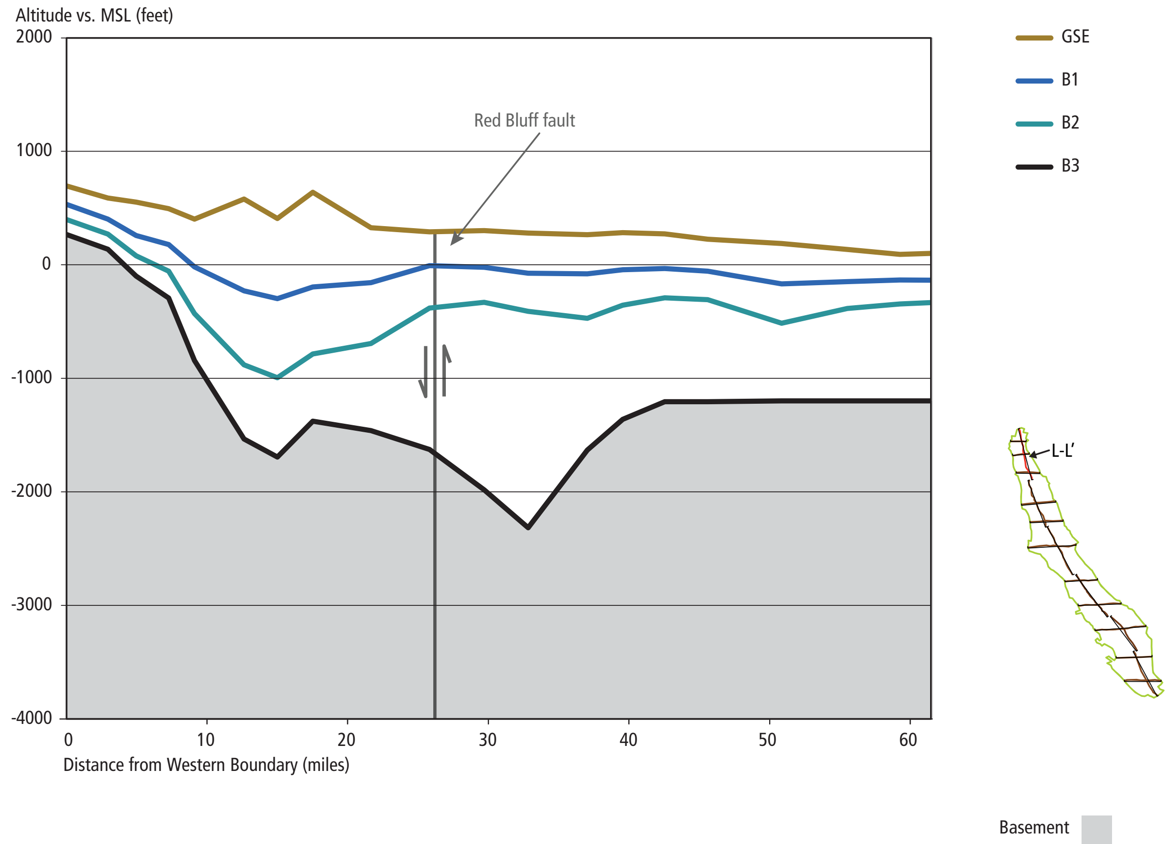


Figure 12M. C2VSim cross section M-M'

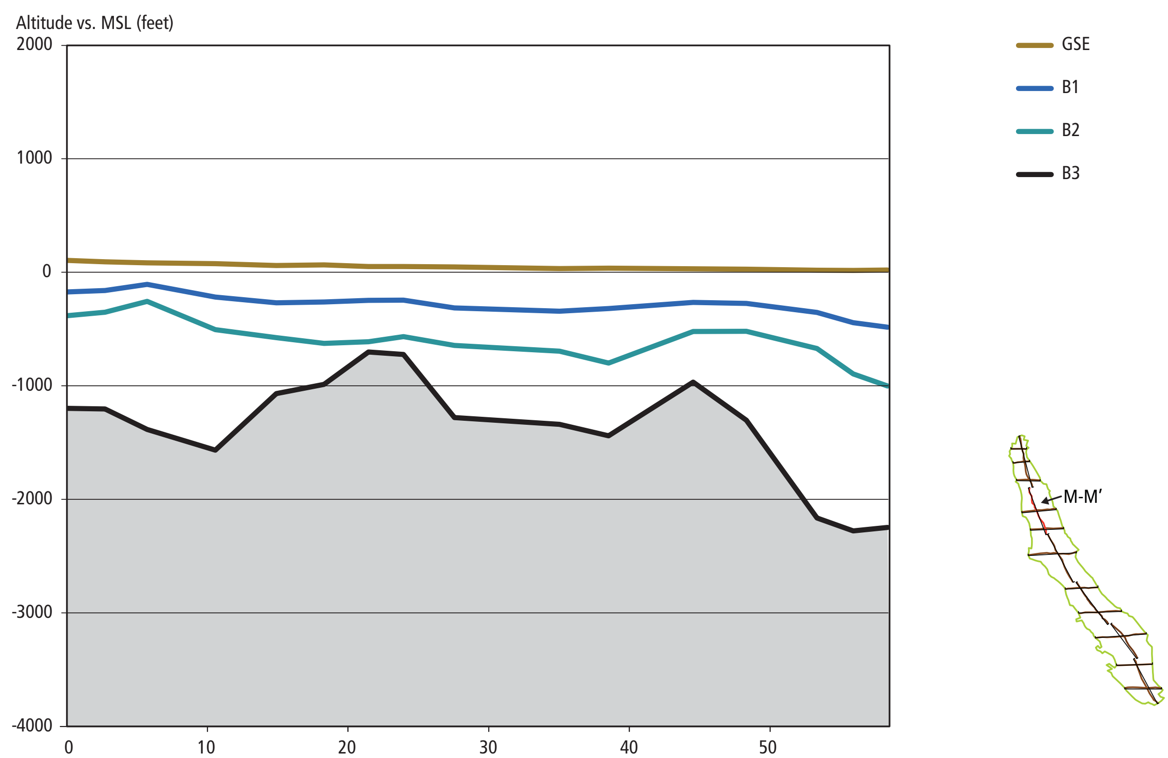


Figure 12N. C2VSim cross section N-N'

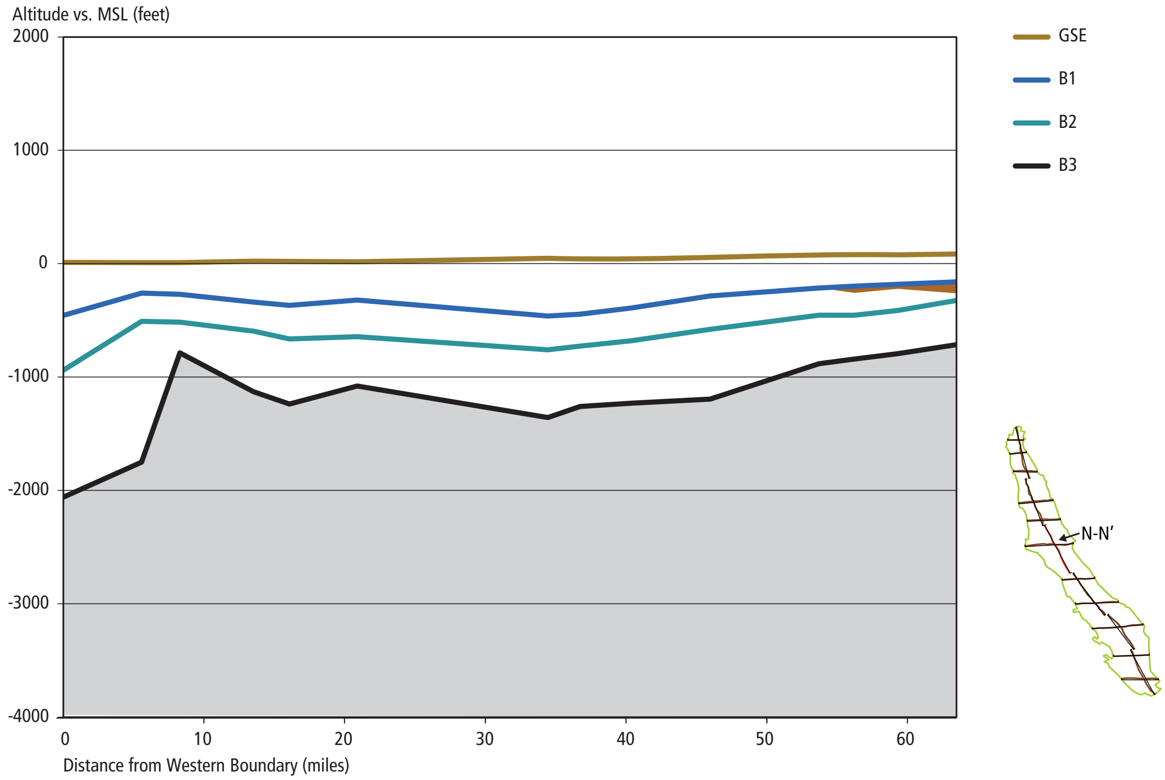


Figure 12O. C2VSim cross section O-O'

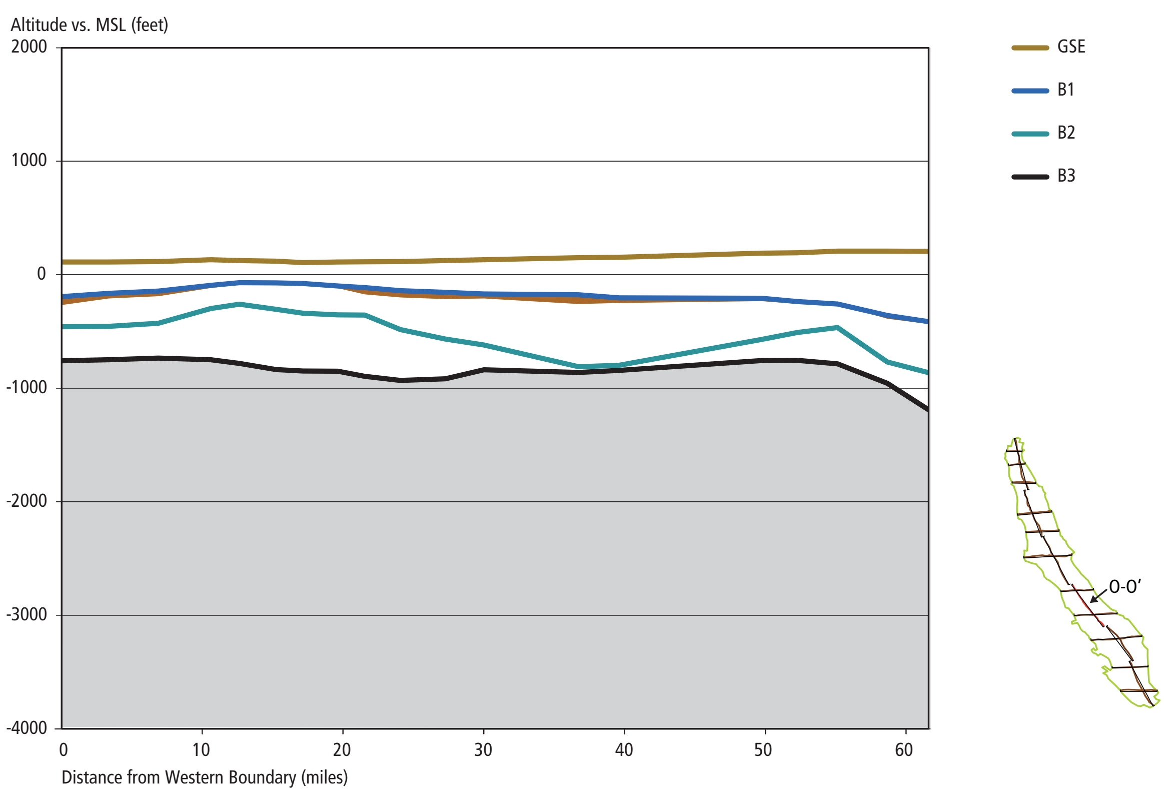
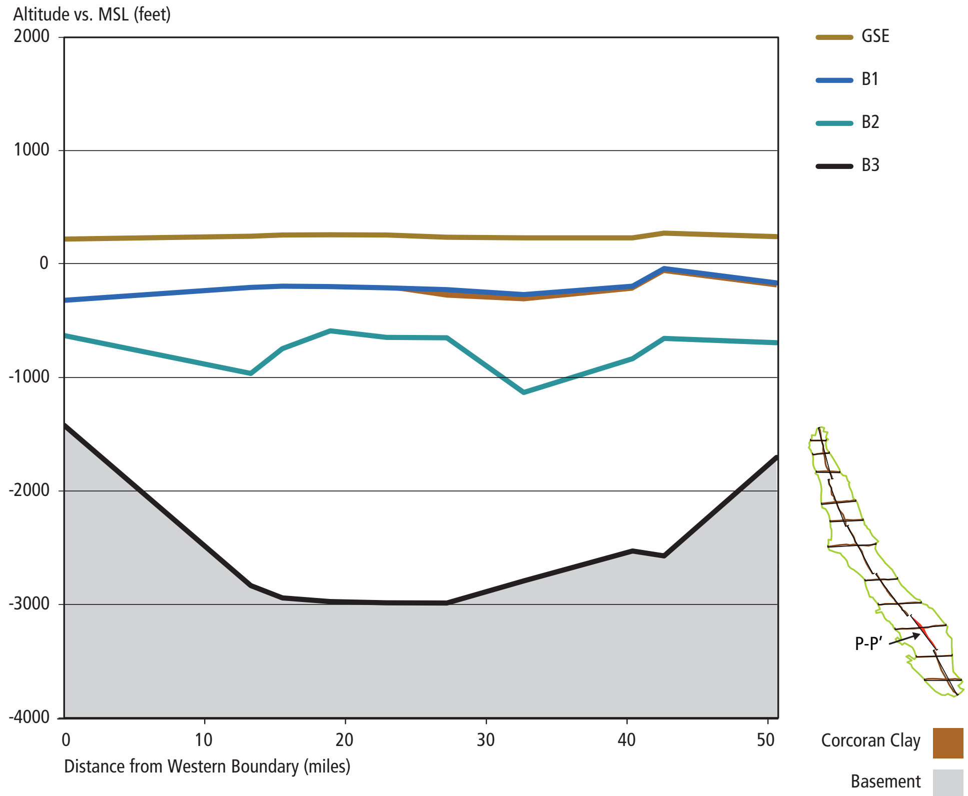


Figure 12P. C2VSim cross section P-P'



The land surface altitude was derived from a digital elevation model of California. The base of the top model layer was generally defined as the top of the Corcoran Clay unit, where present, or the presumed transition from the unconfined to the confined groundwater pumping zone based on well completion reports. The base of the second layer was generally defined as the bottom of the confined pumping zone based on well completion reports. The base of the bottom layer was generally defined as either the top of the basement complex (relatively impermeable rocks) or the base of fresh water (CH2M Hill and S.S. Papadopouos and Associates, 2006).

River configuration

The Pre-processor River Configuration File CVstream.dat contains a section describing the river network as a series of river reaches with their corresponding river nodes and the coincident groundwater nodes (which establish the x-y coordinates of each river node), followed by a section listing the river bed altitude and depth-flow rating table for each river node. IWFM simulates rivers as one-dimensional line segments connecting river nodes along a reach. Flows are routed through the entire network in each simulation time step. C2VSim model grid has 75 river reaches (NRH = 75) with 449 nodes (NR = 449). The rating table for each river node has five data points (NRTB = 5). The river reaches are detailed in figure 4 and table 5, and the river nodes are shown in figure 5.

Table 5. River reaches.

Reach	River Name	Reach	River Name
1	Kern River	39	Sacramento River
2	Kings River	40	Antelope Creek
3	Kings River (S. Fork)	41	Sacramento River
4	Fresno Slough	42	Elder Creek
5	Kaweah River	43	Mill Creek
6	Tule River	44	Sacramento River
7	San Joaquin River	45	Thomes Creek
8	San Joaquin River	46	Sacramento River
9	Fresno River	47	Deer Creek
10	San Joaquin River	48	Sacramento River
11	Chowchilla River	49	Stony Creek
12	San Joaquin River	50	Big Chico Creek
13	Deadman's Creek	51	Sacramento River
14	San Joaquin River	52	Butte Creek
15	Bear Creek	53	Sacramento River
16	San Joaquin River	54	Glenn Colusa Canal (inactive)
17	Merced River	55	Colusa Basin Drainage Canal
18	San Joaquin River	56	Colusa Basin Drainage Canal
19	Orestiba Creek	57	Sacramento River
20	San Joaquin River	58	Sutter Bypass
21	Tuolumne River	59	Feather River
22	San Joaquin River	60	Yuba River
23	Stanislaus River	61	Feather River
24	San Joaquin River	62	Bear River
25	Calaveras River	63	Feather River
26	San Joaquin River	64	Feather River
27	Mokelumne River	65	Sacramento River
28	Dry Creek	66	American River
29	Cosumnes River	67	Sacramento River
30	Mokelumne (South)	68	Cache Creek
31	San Jouquin River	69	Putah Creek
32	Sacramento River	70	Yolo Bypass - Cache Slough
33	Cow Creek	71	Sacramento River
34	Sacramento River	72	Sacramento-San Joaquin Rivers
35	Cottonwood Creek	73	Suisun Marsh
36	Battle Creek	74	Sacramento-San Joaquin Rivers
37	Sacramento River	75	Kern River Flood Channel
38	Paynes Creek		

The first section of the River Configuration File contains a list of the 75 river reaches in sequential order. The description of each river reach starts with a line listing the reach number (ID), upstream river node number (IBUR), downstream river node number (IBDR), and the destination of outflow from the reach (IDWN). A positive IDWN value indicates the river node that receives outflow from this reach, a negative value indicates flows from the reach discharge to a lake (the absolute value of IDWN is the lake number), and a value of "0" indicates flows from the reach discharge outside the model boundary. The individual river nodes that comprise the reach are then listed in sequential order, with the river node number (IRV) followed by the co-located groundwater node number (IGW) and the model subregion the river node is assigned to (IRGST).

The second section of the River Configuration File lists the stream bottom elevations and rating tables for the river nodes. Two conversion factors and the time unit in HES-DSS format are listed at the beginning of this section. Stream bottom elevations are listed in feet, so the conversion factor FACTLT = 1. Rating table flow rates are listed in units of cubic feet per second (CFS), so the conversion factor FACTQ = 60 converts these to cubic feet per minute, and the time unit in HEC-DSS format is TUNIT = "1min". The information for each river node is listed sequentially. The first line of this specification lists the river node number (ID), and the river bottom elevation (BOTR), and the first two rating table points of river depth (HRTB) and corresponding flow rate (QRTB) which are both generally set to zero. The next four lines list the remaining depth-flow points of the rating table (HRTB and QRTB) for this river node. The final two points of the rating table establish the slope used for flows above the highest value in the table. This is repeated for each of the 449 river nodes. Addendum A.3.1 contains a list of river reaches, Addendum A.3.2 contains a list of river nodes and corresponding groundwater nodes and river reaches for each, and Addendum A.3.3 contains the rating table for each river node.

Lake configuration

The Pre-processor Lake Configuration File CVlake.dat describes the lakes simulated in C2VSim. C2VSim has two lakes (NLAKE = 2) comprising a total of 10 model elements (NTELAKE = 10). The next section lists the lakes in sequential order. The first line of each lake description contains the lake number (ID) and the destination of lake outflow (INLAKE). If lake outflow flows to another lake, INLAKE is positive and the value of INLAKE is the lake number; if outflow flows to a river node, INLAKE is negative and the absolute value of INLAKE is the river node number; and if outflow leaves the model area, INLAKE is "0". After INLAKE the number of model elements that comprise the lake (NELAKE), and the number of the first lake model element are listed, with the remaining model elements listed on subsequent lines.

C2VSim simulates Buena Vista Lake in Kern County and Tulare Lake in Tulare and Kings Counties. Buena Vista Lake, which is composed of four model elements, receives flow from the Kern River through a bypass (number 11; all flows are set to zero), and discharges flow to the north-flowing Kern River Flood Channel. Tulare Lake is composed of six model elements, and receives flow from the Kings River South Fork, Tule River, Kaweah River, and Kern River Flood Channel. Tulare Lake discharges through a flow reversal on the Kings River South Fork and then via Fresno Slough, the James Bypass and the Mendota Pool to the San Joaquin River; IWFM can not simulate bidirectional flow along a river reach, so this discharge is simulated by specifying that outflow goes to a river node on Fresno Slough. Addendum A.4 lists the lake specifications, and figure 1 shows the location of the two lakes.

Wells

The Pre-processor Well Data File CVWells.dat lists the locations and characteristics of individual pumping or injection wells. This file is used to specify urban pumping locations in C2VSim (figure 13). The file begins with the number of wells listed in the file (NWELL=133), a factor to convert well coordinates into simulation length units (FACTCX = 3.2808 for converting meters to feet), and conversion factors for well diameter (FACTRW = 1.0) and well perforation depths (FACTLT = 1.0). The wells are then specified in sequential order (ID), with the coordinates (XWELL and YWELL), diameter (RWELL), and altitude of the perforation top and bottom in feet above a datum (PERFT, PERFB). Addendum A.5 lists the urban pumping well specifications.

Element characteristics

The Pre-processor Element Characteristics File CVcharac.dat contains static hydrologic characteristics of each model element. One row for each element lists the element number (IE), precipitation station (IRNE), precipitation multiplier (FRNE), river node receiving precipitation runoff and irrigation return flow (ISTE), subregion (IRGE) and subgroup (ISGE) that the element belongs to, and the soil infiltration factor (ISOILE). For C2VSim, the precipitation station number IRNE

Figure 13. C2VSim coarse grid with urban pumping wells.

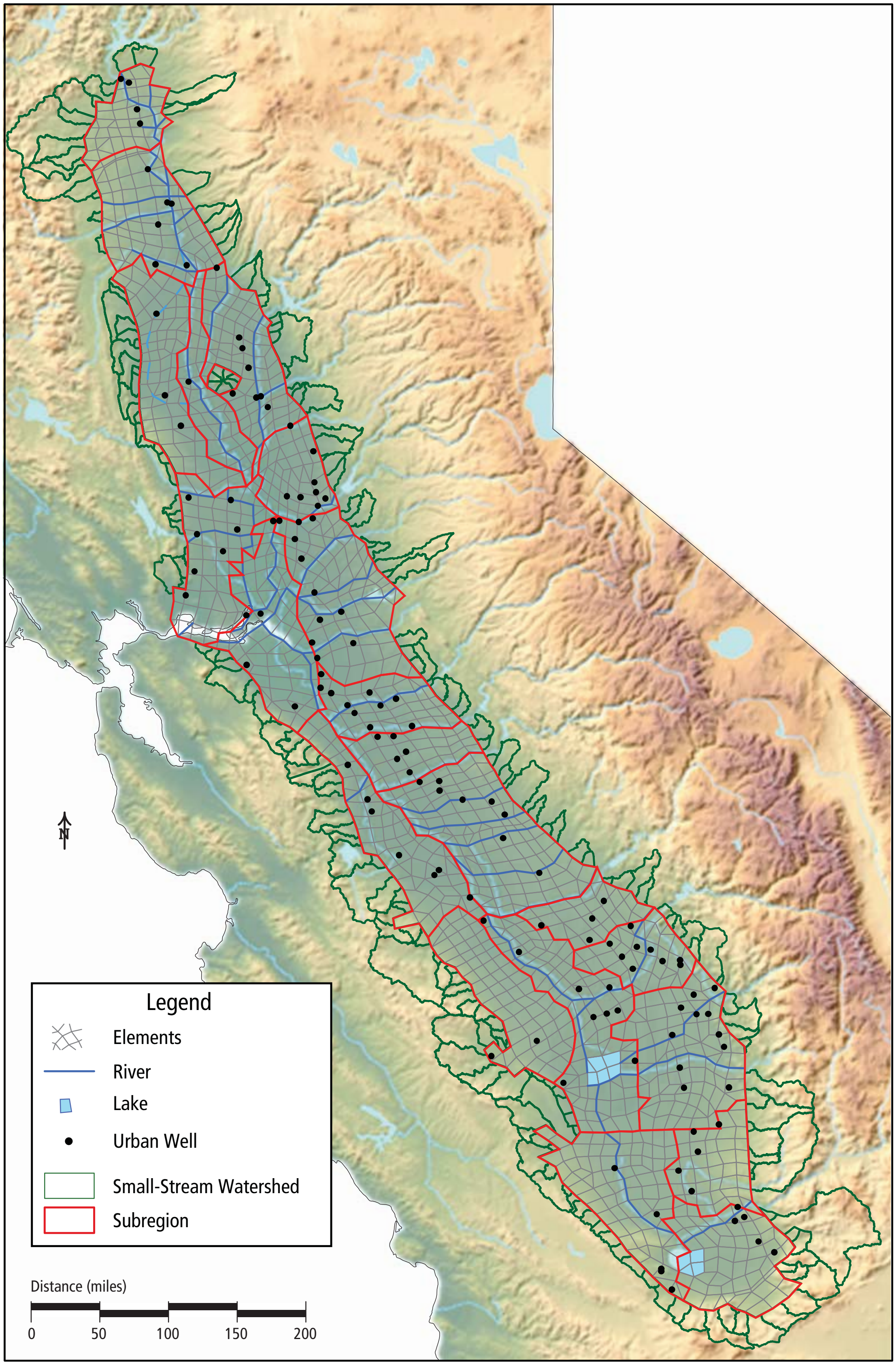


Table 6. Soil characteristics employed by the Integrated Water Flow Model.

Soil Group	ISOILE	Properties
A	1	High infiltration rate (sands and gravels)
B	2	Moderate infiltration rate (mixed fine- and coarse-textured soils)
C	3	High runoff potential (fine-textured sols)
D	4	Semi-pervious to impervious (clay)

corresponds to the column number in the Simulation Precipitation Data File that contains precipitation values for this element. C2VSim Precipitation Data File CVprecip.dat contains one value for each model element, so the multiplier FRNE = 1 for all elements. The river node receiving runoff and return flow (ISTE) was identified using the USGS topographic maps of California. For C2VSim, the element subregion and subgroup are identical (IRGE = ISGE). The soil infiltration factor ISOILE is a numerical representation of the hydrologic soil group (A = 1, B = 2, C = 3, D = 4) for each element and was determined as the area-weighted average hydrologic soil group by intersecting a shapefile of the model grid with a shapefile of the USDA Natural Resource Conservation Service (NRCS) Soil Survey Geographic (SSURGO) database (U.S. Department of Agriculture, 2004b), with the four letter-based soil groups converted to the corresponding numerical values (figure 7). The runoff characteristics for each model element are therefore specified using an ISOILE value between 1.0 and 4.0, as described in table 6. When IWFM reads the ISOILE values, it rounds each non-integer value to the nearest integer value to determine the soil group. Addendum A.2 contains the characteristic values for each element for C2VSim.

Output files

The Pre-processor produces one binary file and one ASCII text file. The binary file CVpreout.bin contains the model framework and is read by the IWFM Simulation program. The ASCII output file PreprocessorMessages.out provides a range of information for the model user. It is good practice to review this file after running the Pre-processor. General information includes the project title (read from the main input file CVpre.in), the date and time the program was run, a list of the input files, and any warning or error messages. Subregion areas, element areas, and the area corresponding to each node are listed. Additional information listed for each node includes whether each aquifer layer is active or inactive; the number of active aquifer layers; and the top and bottom altitudes of each aquifer layer. Information for each river reach is also listed, along with any non-zero components of the conductance matrix.

Running C2VSim – The IWFM Simulation Program

This section describes the Simulation input files for C2VSim, which specify transient components of Central Valley hydrology. The IWFM Simulation program reads these files and simulates the movement of water through the land surface, surface water and groundwater flow systems for the specified time period. C2VSim runs from October 1, 1921 through September 30, 2009 using a monthly time step. The Simulation program produces both ASCII text and binary output files. The binary files are read by the IWFM Budget and Z-Budget programs, which produce tables of simulation results. Subsequent sections of this report describe the use of the binary output files in the IWFM Budget and Z-Budget programs.

Broadly speaking, the C2VSim model presented in this report can be used in two ways: historical and current hydrology can be investigated using the input and output files of the existing model, or the hydrologic impacts of a proposed scenario can be investigated by modifying one or more of the input files. This section describes each input file, and in some cases provides examples of the types of information that can be obtained from these files.

Table 7. Simulation program input and output files.

No.	File Name	Type	File contents
Input files			
5	CVpreout.bin	Binary	Binary input generated by pre-processor
7	CVparam.dat	Text	Hydrologic parameters
8	CVbound.dat	Text	Boundary condition data file
9	[not used]	Text	Time series boundary conditions data file
10	CVprint.dat	Text	Print control file
11	CVinit_1921.dat	Text	Initial aquifer heads and pre-consolidation heads
12	CVsupplyadj.dat	Text	Supply adjustment specification data file
13	CVlanduse.dat	Text	Land use data file
14	CVcropacre.dat	Text	Crop acreage data file
15	CVprecip.dat	Text	Precipitation data file
16	CVevapot.dat	Text	Evapotranspiration data file
17	CVtiledrn.dat	Text	Tile drain specification data file
18	CVurbanspec.dat	Text	Urban water use specification data file
19	[not used]	Text	Agricultural water supply requirement data
20	CVurbandem.dat	Text	Urban water demand file
21	CVinflows.dat	Text	River inflow data file
22	CVcropdem.dat	Text	Crop demand data file
23	CVPuSp.dat	Text	Pumping specification data file
24	CVpump.dat	Text	Pumping data file
25	Cvdivspec.dat	Text	Surface water diversion specification file
26	CVdiversions.dat	Text	Surface water diversion data file
27	CVIrFr.dat	Text	Irrigation fraction data file
28	CVmaxlake.dat	Text	Maximum lake elevations data file
29	CVruf.dat	Text	Irrigation water re-use factor data file
30	[not used]	Text	Aquifer parameter over-write data file

Table 7. Simulation program input and output files, continued.

No.	File Name	Type	File contents
Output files			
31	CVZB.bin	Binary	Binary output for groundwater zone budget
32	CVsmwshed.bin	Binary	Binary output for small watershed flow components
33	[not used]	Binary	Binary output for element sub-group details
34	Cvdiverdtl.bin	Binary	Binary output for diversion details
35	CVstreamrch.bin	Binary	Binary output for stream budget by reach
36	CVlake.bin	Binary	Binary output for lake budget
37	CVlandwater.bin	Binary	Binary output for land and water use budget
38	CVstream.bin	Binary	Binary output for stream budget
39	CVrootzn.bin	Binary	Binary output for root zone moisture budget
40	Cvground.bin	Binary	Binary output for groundwater budget
41	CVSubsHyd.out	Text	Subdicence hydrograph output file
42	CVAvgET.out	Text	Virtual crop characteristics output file
43	[not used]	Text	Element face flow output file
44	[not used]	Text	Boundary flow output file
45	CVtiledrn.out	Text	Tile drain/subsurface irrigation hydrograph
46	CVSWhyd.out	Text	Stream flow hydrograph
47	CVGWhyd.out	Text	Groundwater level hydrograph
48	CVGWheadall.out	Text	Groundwater level output at every model node
49	[not used]	Text	Layer vertical flow
50	CVGWheadTecPlot.out	Text	Groundwater heads for TecPlot
51	CVSubsidTecPlot.out	Text	Subsidence output for TecPlot
52	CVfinallist.out	Text	Final simulation results

Input Files

The main Simulation Input File lists all input files read by the Simulation program and all output files to be produced. Lines that begin with the 'C', 'c' or '*' characters in the first character position are treated as comments and are ignored by the Simulation program. For C2VSim, lines describing the input file are commented out with the 'C' character, and optional data that is not used in the model is commented out with the '*' character. The portion of any line after a forward slash character '/' is also treated as a comment.

Simulation Main Input File

The Simulation Main Input File contains a list of the Simulation input and output files (each with a unique unit number), several control flags, starting and ending times of the simulation period, and factors to convert internal length and area units to output units. The Simulation Main Input File CVsim.in, used for the simulation period October 1921 through September 2009, is described here.

The first three non-comment lines of the Simulation Main Input File are title lines that are placed in the main Simulation output file for future reference. The input and output file section has 51 lines corresponding to file unit numbers 2 through 52. Lines are read up to a slash character '/', after which comments can be entered. These describe each input file type, including the unit number, a brief description of the file, and whether the file is required or is optional. The Simulation program will ignore files for which the file name location is blank (up to the slash character), or for which the file name is commented out with a slash character. C2VSim uses 21 input data files, plus the binary file created using the IWFM Pre-processor program, and produces one binary file for the IWFM Z-Budget program, eight binary files for the Budget program, four text files with time-series hydrographs, two text files for the TecplotTM program, one text file containing final conditions, and one text file (SimulationMessages.out) detailing the simulation progress. SimulationMessages.out contains information listing the simulation input files, aquifer properties, solver iterations for each time step, warnings and error messages, and the total simulation time. The other input and output files for the basic C2VSim simulation are listed in table 7 and are described later in this section of the report.

The next section of the Simulation Main Input File lists the beginning date and time for the simulation. C2VSim uses the IWFM time-tracking option, which allows all input data to be listed with corresponding dates; this feature greatly facilitates model development and use. In IWFM, all dates and times are listed as the end point of a time period. Thus the starting time for the simulation is listed as the last minute of the day before the simulation begins. The initial time for C2VSim simulation is listed as 09/30/1921_24:00 (input item BDT), and the simulation commences immediately after this moment in time, or immediately after midnight on the morning of October 1, 1921. The simulation time step (UNITT) of one month is indicated as '1mon', using HEC-DSS terminology, and the ending time (EDT) is 09/30/2009_24:00. The alternative section for no time tracking is ignored in C2VSim, and entry lines for this section are commented out using the '*' character.

The Output and Debugging Options section has two lines. The first holds the value for KDEB, which specifies what information the Simulation program will write out. KDEB can be set to 2 to write detailed messages to the screen as the program runs, to 1 to write aquifer parameter values for each model node to the SimulationMessages.out file, or to 0 to do neither. The value of CACHE controls how often the Simulation program writes model results to output files; a larger value of CACHE generally corresponds to shorter run times. If CACHE is set to 5000000, then the Simulation program stores 5 million Simulation result values in a memory buffer, pausing to write them to the output files when the buffer is full. If CACHE is set to 1, the Simulation program bypasses the buffer and writes results directly to the output files. Generally a CACHE value of 5000000 has been found to reduce run times without over-running memory limits. If a model is being tested after making modifications to one or more input files, and the user wants to closely monitor the simulation progress, a CACHE value of 1 and a KDEB value of 2 can be used.

The Output Unit Control section of the Simulation Input File contains output units and required conversion factors. C2VSim uses a length unit of feet and a time unit of one month, as entered in the Pre-processor input file, and thus internal calculations use an area unit of square feet, a volume unit of cubic feet and a volumetric flow rate of cubic feet per month. The factors in this section of the input file specify how to convert values from these internal units to the desired output units, and the accompanying labels for the desired output unit types, which are written directly to the output files. The output length unit for C2VSim is feet, so FACTLTOU = 1 and UNITLTOU = 'FEET'. The output area is acres, so FACTAROU = 0.000022957 to convert from square feet to acres, and UNITAROU = 'ACRES'. The output volume unit is acre-feet, so FACTVLOU = 0.000022957 to convert from cubic feet to acre-feet, and UNITVLOU = 'ACRE-FEET'. The output volumetric flow rate is acre-feet per month, so FACTVROU = 0.000022957 to convert from cubic feet per month to acre-feet per month, and UNITVROU = 'AC-FT/MON'. With these conversion factors, the input and output area unit is acres, the volume unit is acre-feet, and the volumetric rate unit is acre-feet per month.

The Solution Scheme Control section contains flags and numerical values that control the behavior of the nonlinear solver. The first input value is a flag to select one of the two solvers: MSOLVE = 1 selects the Successive Over-Relaxation (SOR) method and MSOLVE = 2 selects the Generalized Preconditioned Conjugate Gradient (GPCG) method. The GPCG solver is much faster than the SOR solver for most situations, but in some cases the SOR solver may work when the GPCG solver will not converge. The value of RELAX is used by the SOR solver and ignored by the GPCG solver (but must be included in either case); C2VSim has been found to perform well for values of RELAX between 1.05 and 1.15 when the SOR solver is used. Three iteration parameters specify the maximum number of iterations to be performed before the model exits. The maximum number of iterations for the solution of the system of equations, MXITER = 2000 for the basic C2VSim model. The solver generally converges in less than 10 iterations in each time step, and this number is rarely approached except perhaps in the first time step, or when a severe perturbation is placed on the system. The maximum number of iterations for the nonlinear soil moisture solution, MXITERSM = 150, and the maximum number of iterations for supply adjustment, MXITERSP = 50, are also specified in this section. Three convergence parameters specify how precise the iterative solutions are before the program moves on to the next time step: the convergence criteria for groundwater, stream and lake head differences, STOPC = 0.001 foot; the convergence criteria for soil moisture difference, STOPCSM = 0.0001 foot; and the fraction of water demand to be used as the convergence criteria for iterative supply adjustment, STOPCSP = 0.001 (0.1%).

The Water Budget Control Options are in the final section of the Simulation Main Input File. The value of KOPTDM = 1 in C2VSim indicates that agricultural water supply requirements are calculated by the Simulation program from soil moisture, evapotranspiration and irrigation efficiency information. The item KOPTDV has two digits, each of which has a specific meaning. The first digit can have a value of 0 or 1, and indicates whether the Simulation program is to internally calculate groundwater pumping to meet the residual water demand (first digit = 1), or it is to use the values read from the pumpage input file (first digit = 0). The second digit can have a value of 0, 1 or 2, and indicates whether surface water diversions are adjusted to meet total water demand (second digit = 2), surface water diversions are adjusted to meet total demands after using groundwater (second digit = 1), or surface water diversions are not adjusted (second digit = 0). C2VSim uses KOPTDV = '10', indicating the surface water diversions are read directly from an input file with no adjustment, and initial estimates of groundwater pumping are read from an input file and then adjusted to meet the total water demand. The final item NCROP = 14 indicates that the agricultural land use category for C2VSim has 14 agricultural crop types.

Parameter Data File

The Simulation Parameter Data File CVparam.dat contains parameters describing the hydraulic properties of the aquifer's saturated and unsaturated zones, the land surface, small-stream watersheds, river beds, lake beds, urban water use and agricultural crop rooting depths. These parameters were calibrated with the PEST parameter estimation software (Doherty, 2004) using a set of utility programs that interface PEST with the IWFM programs.

Aquifer Parameters

The first section of the Parameter Data File contains parameter values for the finite element grid for the saturated portion of the aquifer. The IWFM Simulation program allows aquifer parameters to be specified using either parametric grids (NGROUP > 0) or by specifying the values at each node (NGROUP = 0). Parameter values were specified at each node in C2VSim, so NGROUP = 0.

Eleven aquifer parameter conversion factors are specified, one to convert parametric grid length units to simulation units, one for each of seven parameter types, one for each of two interbed thickness parameter types and one for pre-compaction hydraulic head. Three time units are also specified for the three hydraulic conductivity parameter types. Nodal coordinates are specified in length units of meters in the Preprocessor Nodal X-Y Coordinate File, so the parametric grid coordinates unit conversion factor FX is set to 3.281 to convert from meters to feet. All parameter values in the Parameter Data File are specified in length units of feet and a time unit of one month (as specified in the Pre-processor input files), so the ten parameter-specific unit conversion factors are all set to 1, and the three time conversion factors TUNITKH, TUNITV and TUNITL are all set to '1mon'. The Parametric Grid section for aquifer parameter data is not used in the basic C2VSim model, so each of the data lines is commented out using an asterisk.

The Aquifer Parameter Definition section holds a table with parameter values for each finite element aquifer node. Values are listed by finite element node, for each layer from the top layer (number 1) to the bottom layer (number 3). Values for ten items are listed, seven parameters and three aquifer properties. The seven parameters are aquifer horizontal hydraulic conductivity (PKH, ft/mo), aquifer specific storage (PS, 1/ft), aquifer specific yield (PN, ft/ft), aquitard vertical hydraulic conductivity (PV, ft/mo), aquifer vertical hydraulic conductivity (PL, ft/mo), aquifer interbed elastic storage coefficient (SCE, 1/ft), and aquifer interbed inelastic storage coefficient (SCI, 1/ft). The three aquifer properties are initial aquifer interbed thickness (DC, ft), minimum aquifer interbed thickness (DCMIN, ft), and initial aquifer pre-compaction hydraulic head (HC, ft). Aquitard vertical hydraulic conductivity is multiplied by aquitard thickness to yield a leakance value, and thus is only important at locations where the aquitard thickness is greater than zero. Values for the seven aquifer parameters were determined through model calibration. Values for the three aquifer properties were taken from the CVGSM model (James M. Montgomery Consulting Engineers, 1990B).

The next part of the Aquifer Parameters section contains hydraulic conductivity anomalies. These are used to specify elements where faults serve as barriers to the horizontal flow of groundwater. Two faults are simulated in C2VSim by incorporating narrow grid elements: the Red Bluff Arch in the northern part of the model domain (elements 55-58) and the White Wolf Fault at the southern end of the model domain (elements 1383-1385). For each specified anomaly, the element number is listed (IEBK), followed by the horizontal hydraulic conductivity (ft/mo) to be used at each of the nodes of the specified element for each model layer.

Unsaturated Zone Parameters

The next section of the Parameter Data File describes the properties of the unsaturated zone. Two unsaturated zone layers are used, so NUNSAT = 2. Unsaturated zone parameters can be specified using either parametric grids (NGROUP > 0) or by specifying the values at each node (NGROUP = 0). Unsaturated zone parameter values are specified at each model node, so NGROUP = 0. Four unsaturated zone parameter conversion factors are specified, one to convert parametric grid length units to simulation units (FX), and one for each of three parameter types, FD for thickness, FN for porosity, and FL for hydraulic conductivity. The time unit of the hydraulic conductivity values, TUNIT, is specified in HEC-DSS format. Nodal coordinates are specified in length units of meters in the Preprocessor Nodal X-Y Coordinate File, so the parametric grid coordinates unit conversion factor FX is set to 3.281 to convert from meters to feet. The three parameter-specific unit conversion factors FD, FN and FL are all set to 1, and the time conversion factor TUNIT is set to '1mon'. The Unsaturated Zone Parametric Grid section is not used, so each of the data lines is commented out using an asterisk.

The Unsaturated Zone Parameter Definition section has one row for each model element. Each row contains parameter values for thickness (PD, ft), porosity (PN, ft/ft), and vertical saturated hydraulic conductivity (PL, ft/mo) listed for each unsaturated-zone layer. C2VSim has two unsaturated zone layers, so PD, PN and PL are listed twice on each line. Layer thicknesses were determined as half the distance between the initial water table altitude and the land surface.

Soil Moisture Routing

The next section of the Parameter Data File contains soil moisture routing parameters by hydrologic soil group (A, B, C and D) for each model subregion. The IWFM Simulation program has two options for partitioning excess soil moisture (i.e. moisture above field capacity) to deep percolation: specifying the fraction of excess soil moisture that will become deep percolation, with the remainder becoming overland flow, or specifying the vertical saturated hydraulic conductivity of the root zone to compute deep percolation using a physically-based approach. C2VSim uses the first option, specifying a factor to partition excess soil moisture between deep percolation and surface runoff (KUSAGE = 0). Parameter values are entered in length units of feet and time units of one month, so the conversion factors are FACT = 1 and TUNIT = '1mon'.

Soil moisture routing parameter values are entered in a table with one row for each model subregion. Each row has four sections, each holding the parameters for one hydrologic soil group (A, B, C and D). The section for each hydrologic soil group has seven items: three factors and four curve numbers. The three factors are the field capacity (FC, ft/ft), total porosity (EF, ft/ft), and the fraction of excess soil moisture that will become deep percolation (K). Four runoff curve numbers converted to model length units (CN*) are listed for each soil group for each of the four land use types: (1) agricultural, (2) urban, (3) native vegetation and (4) riparian vegetation. Model curve numbers in length units of feet (CN*) can be related to the standard NRCS curve numbers in length units of inches (CN) using the following equation:

$$CN^* = (12000 \times CN)/(110 \times CN+1000)$$

Field capacity and total porosity values were determined as area-weighted averages from the USDA Natural Resource Conservation Service (NRCS) Soil Survey Geographic (SSURGO) database (U.S. Department of Agriculture, 2004B). Initial curve number values (CN) for representative land use types and hydrologic soil groups were obtained from USDA NRCS TR-55 (U.S. Department of Agriculture, 1986) and converted to model length units (CN*), and were then adjusted during model calibration.

Small-Stream Watershed Data

The Small-Stream Watershed Data section contains soil moisture routing parameters and partitioning coefficients for routing precipitation through tributary watersheds defined in the Boundary Conditions File. Six factors are specified at the beginning of this section. C2VSim has 210 small-stream watersheds (NSW = 210). All parameters are in simulation length and time units of feet and months, so FACTL = 1, FACTK = 1, TUNITK = '1mon', FACTT = 1, and TUNITT = '1mon'.

The parameter data table has one line for each small-stream watershed, which begins with the small-stream watershed number, followed by ten items. The first two items are the column of the precipitation data file that contains precipitation for this watershed, and the precipitation multiplier, which is 1 for all small-stream watersheds. Next, the soil moisture parameters are listed: field capacity (FLDCAS, ft/ft), total porosity (TPOROS, ft/ft), root-zone depth (CROOT, ft), the fraction of excess soil moisture routed to deep percolation (SOILKS), and the curve number converted to model length units (CN*). The last three items are the threshold value of groundwater depth above which small-stream watershed groundwater storage contributes to surface runoff (GWSOS, ft), the recession coefficient for surface outflow (SWKS, 1/mo), and the recession coefficient for groundwater base outflow (1/mo). The initial parameter values for field capacity, total porosity and hydrologic soil group for each small-stream watershed were determined as area-weighted averages from the SSURGO map of California (U.S. Department of Agriculture, 2004B) and were then adjusted during model calibration. Representative curve number values (CN) were obtained from USDA NRCS TR-55 (U.S. Department of Agriculture, 1986) and converted to model length units (CN*), and were then adjusted during model calibration.

Stream Bed Parameters

The Stream Bed Parameters section of the Parameter Data File contains stream-bed conductance parameters for the river nodes defined in the Preprocessor River Configuration File. This section begins with three items, a stream-bed conductivity length units conversion factor (FACTK = 1), the conductivity time unit (TUNITK = 1mon), and a stream-bed thickness conversion factor (FACTL = 1). The parameter data table has one line for each river node. Each line contains the river node number (IR), stream-bed vertical hydraulic conductivity (CSTRM, ft/mo), stream-bed thickness (DSTRM, ft), and wetted perimeter (WETPR, ft). Stream-bed conductance is a function of both the stream-bed vertical hydraulic conductivity and the stream-bed thickness. In C2VSim, CSTRM contains the stream-bed conductance value, and all stream-bed thicknesses are set equal to 1.0 ft. Wetted perimeter values were determined from the CVGSM model (James M. Montgomery Consulting Engineers, 1990B) where available, and otherwise by estimating channel widths and depths from topographic maps. This table includes comments to the right side listing the river reach for each river node.

Lake-Bed Parameters

The Lake-Bed Parameters section begins with three items, a conversion factor for lake-bed hydraulic conductivity (FACTK = 1), the time unit of lake-bed hydraulic conductivity (TUNITK = 1mon), and a conversion factor for lake-bed thickness (FACTL = 1). The lake-bed conductance table has one row for each lake, with the lake number (IL), lake-bed hydraulic conductivity (CLAKE, ft/mo), lake-bed thickness (DLAKE, ft), and the column of the lake maximum elevation time-series file containing the lake's maximum elevation (ICHLMAX). Lake-bed conductance is the product of the lake-bed vertical hydraulic conductivity and the lake-bed thickness. In C2VSim, CLAKE contains the lake-bed conductance value, and all lake-bed thicknesses are set equal to 1.0 ft. The Parameter Data File entries include comments on the right side listing the lake name for each lake.

Water Use Parameters

The last section of the Parameter Data File contains water-use parameters and crop rooting depths. The first table in this section has one line for each subregion. Each line has the subregion number (IR), the urban fraction of pervious area to total area (PERV), and the columns of the Irrigation Water Re-use Factors File containing the fraction of agricultural surface runoff and return flow that is re-used (ICRUFAG) and the fraction of urban surface runoff and return flow that is re-used (ICRUFURB). The final column contains a flag specifying the destination of urban return flow (IURIND). In C2VSim, all subregions have an urban pervious fraction of 62% (PERV = 0.62), urban runoff for subregions 1-9 flows to rivers (IURIND = 0), and urban runoff for subregions 10-21 becomes groundwater recharge (IURIND = -1). This is followed by a table listing the rooting depth for each of the 14 agricultural crops and of the other three land-use types. All root depths are in feet, so FACT = 1, and root depths range between 2.0 and 6.0 ft.

Boundary Conditions Data File

The Simulation Boundary Conditions Data File CVbound.dat contains specifications for aquifer system boundary conditions, and specifications of tributary small-stream watersheds that contribute flows from areas outside the model boundary. C2VSim only incorporates small-stream watershed boundary conditions; other than these, the aquifer system has a no-flow boundary.

Boundary conditions are listed in the Boundary Conditions Data File by model layer. Within each layer, they are listed in the following order: specified flux, specified head, rating table, and general head. Since C2VSim does not use any of these boundary conditions, for each model layer, the number of boundary conditions of each type is set to zero (NQB = 0, NHB = 0, NMB = 0, NMTB = 0, and NGB = 0), all conversion factors are set to one (FACT = 1.0, FACTH = 1.0, FACTQ = 1.0, FACTAR = 1.0), and all time unit specifications (TUNIT) are left blank. All data lines are commented out using asterisks.

The IWFM small-stream watershed capability uses an approximate method to simulate surface and subsurface flows from small ungaged watersheds bounding the model domain. The 210 small-stream watersheds in C2VSim were delimited using the California Interagency Watershed Map of 1999 (CalWater 2.2.1, http://www.ca.nrcs.usda.gov/features/calwater/). Areas are specified in acres, and the factor FACTA converts these to square feet (FACTA = 43560). Flows are specified in acre-feet per month, and the factor FACTQ converts these to units of cubic feet per month (FACTQ = 43560). The time unit is specified as one month (TUNIT = '1mon').

The information describing each small-stream watershed is listed with an initial line containing the watershed number, parameter group, area, final discharge destination, and the number of nodes in the discharge stream arc. This is followed by several lines describing the path and properties of the ephemeral stream discharging from the watershed. The first line begins with the watershed identification number (ID). This is followed by the watershed parameter group (IWBS) in the Parameter Data File, which is equal to the watershed ID. The watershed area in acres is listed next (AREAS), followed by the river node that is the final destination of surface runoff (IWBTS). Groundwater nodes may receive small-stream watershed flows as either base flow or as deep percolation of surface flow from the intermittent stream carrying small-stream watershed discharge. The number of groundwater nodes receiving either type of flow is stated (NWB), followed by the node number of the boundary groundwater node adjacent to the small-stream watershed, and the value -1, indicating this node receives base flow. The next lines each list a groundwater node of the intermittent stream, and the maximum recharge rate at that node in acre-feet per month. In C2VSim, the boundary node adjacent to each small-stream watershed is specified to receive base flow, and one or more groundwater nodes are specified to delineate the intermittent stream arc. The groundwater nodes of this arc were delineated to roughly correspond to the path followed by surface water discharging from the watershed (within the limits of the finite element grid) using the USGS topographic map of California. The maximum recharge rate was initially set to 40 acre-feet per month at each node for watersheds north of the Sacramento-San Joaquin Delta and 200 acre-feet per month for watersheds south of this location, and 10 acre-feet per month along the western border of Kern County. The small-stream watershed descriptions are listed in Addendum A.6.

The surface water outflow from eight small-stream watersheds, numbers 105 to 112 is exported from the model by setting the destination river node to '0'. The surface flows from these tributary watersheds are included in the specified inflows for Cottonwood Creek. The small-stream watersheds were retained in the Boundary Conditions Data File to simulate groundwater inflows and recharge from the drainage arcs.

Time Series Boundary Conditions Data File

The Simulation Time Series Boundary Conditions Data File allows the use of time series data for specified-head, specified-flow, and general-head boundary conditions. This capability is not used in C2VSim.

Print Control Data File

The Simulation Print Control Data File contains information specifying the desired time-series hydrographs that will be produced by the Simulation program. Simulated hydrographs can be printed for groundwater wells, stream nodes, tile drains, subsidence extensometers, boundary nodes, and element faces. The C2VSim Print Control Data File CVprint.dat includes locations of simulated groundwater hydrographs at 1387 locations, simulated river flow hydrographs at 39 river nodes, simulated tile drain hydrographs at 11 locations, and simulated subsidence time series at 24 locations. The C2VSim Print Control Data File does not include any boundary node flows or element face flow values. The groundwater hydrographs and stream nodes correspond to the groundwater observation wells and stream gages used to calibrate the model.

The groundwater hydrograph print control specifications section of the Print Control Data File lists the number of hydrographs (NOUTH = 1387) and a factor to convert nodal coordinate length units to model length units. Well coordinates are specified in the same units used in the Pre-processor Nodal Coordinates File, meters, and the conversion factor (FACT = 3.2808) converts these to model length units of feet. The next section lists the information for each groundwater hydrograph location. The first item, IOUTHL, is the model layer. All groundwater hydrograph locations list the corresponding model layer, determined from well logs; alternatively, a value of 0 could be entered to print the average head of all model layers. The next two items list the x- and y-coordinates of the well. Well coordinates are specified in the same units used in the Pre-processor Nodal Coordinates File. The fourth item is a text label that is used by the IWFM-PEST utilities to link model output to corresponding observed head values. Well labels for the first 1145 wells are abbreviated versions of well names from the California well log database, and the remaining 242 wells are paired wells used to calculate vertical head differences between model layers. These groundwater hydrographs were used to calibrate the model.

The river flow hydrograph print control specifications section of the Print Control Data File lists the number of hydrographs (NOUTR = 39) and a factor to choose between flow volume and surface elevation; C2VSim prints flow values (IHSQR = 0). Each river flow hydrograph location is identified by the river node number, and each river node number is followed by a three-letter code that is used by the IWFM-Pest utilities to link model output to corresponding observed flow values. For most river flow hydrographs, this is followed by a short comment field describing the flow location.

The tile drain hydrograph print control specifications section of the Print Control Data File lists the number of tile drain hydrographs (NOUTTD = 11), followed by the groundwater node number of the tile drain. A hydrograph is specified for each modeled tile drain.

The subsidence print control specifications section of the Print Control Data File lists the number of subsidence hydrographs (NOUTS = 24) and a factor to convert nodal coordinate length units to model length units. Well coordinates are specified in the same units used in the Pre-processor Nodal Coordinates File, meters, and the conversion factor (FACT = 3.2808) converts these to model length units of feet. The next section lists the information for each subsidence hydrograph location. The first item, IOUTSL, is the model layer, determined from extensometer metadata. The next two items list the x- and y-coordinates of the extensometer, specified in the same units used in the Pre-processor Nodal Coordinates File.

The boundary node print control section is not used, so the number of hydrographs is set to zero (NOUTB = 0) and the list section is commented out using asterisks. The element face flow print control section is also not used, so the number of element faces is set to zero (NOUTF = 0) and the list section is commented out using asterisks.

Initial Conditions Data File

The Simulation Initial Conditions Data File CVinit_1921.dat contains initial conditions for the simulation starting time (12:00 AM October 1, 1921). These include the initial aquifer head values, the initial soil moisture for the root zone, initial moisture values for the unsaturated zone, and initial moisture values for the small-stream watersheds.

The first section of the Initial Conditions Data File lists the initial groundwater heads for each node by model layer. For each layer, there is a line with the value of FACT, followed by 1393 lines which hold the initial head at each groundwater node. Head values are listed in feet, so the conversion factor FACT = 1 for each model layer. The initial head values for October 1, 1921, were delineated manually based on observed head values and water level maps of Bryan (1923), Mendenhall et al (1916) and California Department of Public Works (undated).

The next section of the Initial Conditions Data File contains initial soil moisture conditions for the root zone, unsaturated zone and small-stream watersheds. These initial values for October 1, 1921 were estimated by starting with initial values of 0, running the model for five years with constant October 1921 values for all model inputs, and taking the state values from the output file CVfinallist.out. Root zone initial soil moisture conditions are listed first. The initial soil moisture is given in feet (FACTSM = 1). There are four lines for each subregion. The first line begins with the subregion ID, and each line contains initial soil moisture values for each of the four land use types (agricultural, urban, native vegetation and riparian vegetation), with one line for each hydrologic soil group (A. B. C and D). Unsaturated zone initial soil moisture conditions are listed next. In C2VSim, these values are in feet, so the conversion factor FACT = 1. There is one line for each model element containing the element ID, followed by the initial soil moisture for each of the two unsaturated zone layers. Small-stream watershed initial soil moisture conditions are listed next. These values are given in feet, so the conversion factor FACT = 1. There is one line for each of the 210 small-stream watersheds which contains the watershed ID, the initial soil moisture content (SOILS, ft/ft), and the initial groundwater storage (GWSTS, ft).

The next section of the Initial Conditions Data File contains initial lake surface elevations. These are given in feet, so the conversion factor FACT = 1. There is one row for each lake which contains the lake number (ILAKE) and the initial lake surface elevation (HLAKE, ft). In C2VSim, each initial lake surface elevation is set equal to the lake bottom elevation.

The next section of the Initial Conditions Data File contains the initial interbed thickness at each groundwater node for each model layer, and the initial preconsolidation head values for land subsidence for each model layer. The values in the Parameter Data File are used to specify these initial conditions, and therefore these items are omitted from the Initial Conditions Data File. This is accomplished by setting the conversion factor FACT to 0 for each model layer, and omitting the lines that would otherwise contain the initial conditions.

When the Simulation program is run, it produces a Final Simulation Results file (file number 51) that can be used as an initial conditions file for subsequent simulations. If, for example, a user was interested in developing a future scenario beginning on October 1, 2009, they could use the file CVfinallist.out produced by the basic C2VSim simulation as their initial conditions file for subsequent model runs.

Supply Adjustment Specifications File

The Simulation Supply Adjustment Specifications File CVsupplyadj.dat contains time-series 'flags' indicating whether groundwater pumping and/or surface water diversions are to be adjusted to meet agricultural demand, urban demand, or both. Supply adjustment is turned on or off using the two-digit variable KOPTDV in the Simulation Input File. The Supply Adjustment Specifications File is required if KOPTDV has any value other than '00'.

The first section of the Supply Adjustment Specifications File has three lines that describe how the data section is constructed. The first item is the number of data columns. In C2VSim, there are 400 columns (NCOLADJ = 200). Time tracking is used , so the second and third items are ignored (NSPADJ = 1, NFQADJ = 1). The fourth item is used when data is stored in a DSS database, and is left blank in C2VSim.

The groundwater pumps for each element are associated with a column in the Supply Adjustment Specifications File via the value of ICADJSK in the Pumping Specification File (CVPuSp.dat). All groundwater pumps are associated with column 1 of the Supply Adjustment Specifications File. Each surface water diversion can be associated with a column in the Supply Adjustment Specification File via the value of ICADJ in the Surface Water Diversion Specifications File (CVdivspec.dat). The supply adjustment specification for each surface water diversions equals th ediversion number.

Each data row begins with the final time period that the data is valid. C2VSim does not fully utilize the functionality of the Supply Adjustment Specification File, and has only one row that is valid for the entire simulation period (with an end date of September 30, 2100). Each data column contains one KADJ value, which is composed of two integers that each act as a 'flag'. The left integer specifies whether or not the supply of agricultural water is to be adjusted, and the right integer specifies whether or not the supply of urban water is to be adjusted. A value of '1' indicates adjustment is allowed, and a value of '0' indicates that adjustment is not allowed. For C2VSim, all KADJ values are set to '11', indicating that groundwater pumping and each of the surface water diversions may be adjusted to meet both agricultural and urban water demands, depending on the value of KOPTDV in the Simulation Input File. This file can be expanded to exert more control over the times and locations in which groundwater pumping and/or surface water diversions are to be adjusted.

Land Use Data Specification File

The Simulation Land Use Data Specification File CVlanduse.dat contains time-series data listing the land use distribution for each model element. Data is listed once for each water year (October 1 through September 30) for water years 1922 through 2009 (October 1921 through September 2009). The indicated date is the date at which the time series ends; thus the first data set is dated 09/30/1922, the last day of water year 1922, and the last data set is dated 09/30/2009, the last day of water year 2009. For simulations that begin after September 1922, the IWFM Simulation program will automatically skip data until it reaches the appropriate time period.

The first section of the Land Use Data Specification File contains four control items. The conversion factor FACTLN converts the specified land areas to simulation area units. Land use areas are specified in units of acres in the C2VSim Land Use Data Specification File, and the conversion factor converts acres to square feet (FACTLN = 43560). The next two items are ignored because time tracking is used (NSPLN = 1 and NFQLN = 1). The fourth item DSSFL is used when data is stored in a DSS database, and is left blank in C2VSim.

The data section of the Land Use Data Specification File contains the land use distribution, with one row for each model element. The first row has the time stamp, and each row has the element number (ID), followed by the acreage in each of the four land use categories (agricultural, urban, native vegetation, and riparian vegetation). The total acreage for each row equals the acreage of the listed element. The annual elemental land use distribution was created by passing the land use distributions for water year 1954, 1980 and 1993 from the CVGSM model (Taghavi and Najmus, 2000), through the Land Use Adjustment Preprocessor (Dogrul 2005). The land use data for C2VSim is too large to list in a textual addendum.

Crop Acreage Data File

The Simulation Crop Acreage Data File CVcropacre.dat contains time-series data by model subregion listing the crop acreages within the agricultural land use and the acreage in each of the other three land use types. C2VSim has 21 subregions corresponding to DWR Depletion Study Areas (DSAs, table 1). The first section of the Crop Acreage Data File contains constants and factors that specify how the data is formatted. The first item is the number of data columns to be read, which is equal to the number of agricultural crops (14) plus three non-agricultural land uses (NCOLCR = 17). Crop areas are specified in units of acres, so the conversion factor converts acres to square feet (FACTCR = 43560). The next two numbers are ignored because time tracking is used (NSPCR = 1 and NFQCR = 1). The final item, DSSFL, is used when data is stored in a DSS database, and is left blank in C2VSim.

The data section contains entries for specified time periods with the time stamp equal to the end of the time period of the data set. C2VSim has data for each water year, so the time stamp is midnight of the last day of the water year (e.g. 09/30/1922_24:00 for water year 1922). The data section contains one row for each of the 21 model subregions. Each row has the subregion number (ID), followed by the acreages of each agricultural crop (ACROP(i), i = 1,2,..14), and the urban, native vegetation, and riparian vegetation acreages (ACROP(i), i = 15, 16, 17). The index values for the 14 agricultural crop types and three other land use types are listed in table 8. Subregional crop acreages for water years 1922 to 2003 were derived from input data sets for the DWR Consumptive Use Model (James M. Montgomery Consulting Engineers, 1990B; CH2M Hill, Inc, 1996; T. Kadir, DWR, personal communication, 2011). Subregional crop acreages for water years 2004 to 2009 were derived from county agricultural commissioners' reports. The Crop Acreage Data File contents are too large to list in a textual addendum.

Table 8. Crop and land use index numbers.

Index	Key	Name
1	PA	Pasture
2	AL	Alfalfa
3	SB	Sugar Beet
4	FI	Field Crops
5	RI	Rice
6	TR	Truck Crops
7	TO	Tomato
8	TH	Tomato (Hand Picked)
9	TM	Tomato (Machine Picked)
10	OR	Orchard
11	GR	Grains
12	VI	Vineyard
13	CO	Cotton
14	SO	Citrus & Olives
15	UR	Urban
16	NV	Native Vegetation
17	RV	Riparian Vegetation

Precipitation Data File

The Simulation Precipitation Data File CVprecip.dat contains a monthly time-series of precipitation data for the period from October 1921 to September 2009. The Precipitation Data File contains one data column for each model element and for each small-stream watershed (NRAIN = 1602). Precipitation rates are specified in inches per month and converted to simulation units of feet per month through the length units conversion factor (FACTRN = 0.08333). The next two items are ignored in C2VSim because time tracking is used (NSPRN = 1 and NFQRN = 1). The fifth item, DSSFL, is used when data is stored in a DSS database, and is left blank in C2VSim.

The precipitation data is listed as a time series with one row for each month from October 1921 through September 2009. These precipitation rates were derived from monthly Parameter-elevation Regressions on Independent Slopes Model (PRISM) values. The first 1392 columns contain monthly precipitation rates for model elements, and the next 210 columns contain precipitation rates for the small-stream watersheds. These precipitation rates were calculated as area-weighted averages from PRISM 2 km x 2 km monthly precipitation grids supplied by Oregon Climate Service (written communication, 2010).

Evapotranspiration Data File

The Simulation Evapotranspiration Data File CVevapot.dat contains crop evapotranspiration rates (ETc) under standard conditions, which represent the net vertical water flux from the land surface and root zone through the upper model boundary. The Evapotranspiration Data File contains evapotranspiration values for each model subregion and each small-stream watershed for specified time steps. Evapotranspiration values are provided for each of 14 crops, three non-agricultural land-use categories, and for bare soil (NEVAP = 18). Evapotranspiration rates are provided in units of inches per month, and converted to simulation units of feet per month through the length units conversion factor (FACTET = 0.08333). The next two items are ignored because time tracking is used (NSPET = 1 and NFQET = 1). The fifth item, DSSFL, is used only when data is stored in a DSS database and, therefore, is left blank.

C2VSim has one set of evapotranspiration values for each calendar month, which are repeated for each simulation year. This is accomplished in IWFM by setting the year to 4000, a flag that indicates the year is to be ignored and only the month and day are to be used to assign data values to time steps. For each time step, 18 evapotranspiration values are listed for each subregion (21 rows) followed by native vegetation and bare soil rates for each small stream watershed group (210 rows). The evapotranspiration values were derived from the DWR Consumptive Use Model (DWR 1979) and represent average crop evapotranspiration rates for each month. The values for a given month are constant through time, a model limitation that reduces the accuracy of the simulated crop water demands.

Tile Drain Specification File

The Simulation Tile Drain Specification File CVtiledrn.dat contains a list of groundwater nodes at which tile drains are located, and the altitudes and conductances of the tile drains. C2VSim has tile drains at eleven groundwater nodes (NTD = 11). Tile drain altitudes are specified in units of feet above datum (FACTH = 1). Tile drain conductances are specified in units of ft2/sec, and the multiplier FACTCDC = 60 converts them to time units of minutes, the units specified by TUNIT = '1min'.

The next section contains one line for each groundwater node with tile drains present. The first item in each row is the groundwater node number combined with a flag indicating the flow direction. For drainage out of the node, the groundwater node number is listed as a negative value. Thus tile drainage outflow from groundwater node 794 is indicated as "–794". The groundwater node number is followed by the drain altitude above datum (ELEVDR in feet), hydraulic conductance of the interface between the aquifer and the drain (CDCDR in ft2/sec), and stream node receiving drain flow (ISTRMDR).

The locations for tile drains were delineated to match on-farm tile drains in the Grasslands Drainers Area to the north of the Westlands Water District. Regional collector drains installed in the Westlands Water District and covering an area of approximately 42,000 are also included, but are commented out as they were in operation only in water years 1982-86, and the IWFM Simulation program cannot turn drains on or off during the simulation. Drain conductances for the Grassland Drainers Area were set to 0.52 ft2/sec.

Urban Water Use Specification File

The Simulation Urban Water Use Specification File CVurbanspec.dat contains data specifying the total fraction of urban water that is used indoors. Data is specified using time tracking, so the values for NSPURBSP and NFQURBSP are not used. The item DSSFL is used only when data is stored in a DSS database, is left blank. Times are listed as year 4000, a flag that indicates the year is to be ignored and only the month and day are to be used to assign data values to time steps, allowing the values to be repeated for each year. For each month, there is one row for each model subregion, containing the subregion number and the fraction of total urban water that is used outdoors. The indoor water use factors (URINDR) for each month are the same for all model subregions, and are listed in table 9.

Table 9. Monthly urban indoor water use fractions.

Month	Indoor Use
October	50%
November	70%
December	80%
January	100%
February	100%
March	60%
April	50%
May	45%
June	40%
July	40%
August	40%
September	40%

Urban Water Demand File

The Simulation Urban Water Demand File CVurbandem.dat contains the urban water demand for each subregion as a time series. Urban water demand includes indoor and outdoor water use for both municipal and industrial uses. Data is entered in units of thousand acre-feet per month, and is converted to the simulation length units of cubic feet per month with a conversion factor (FACTOU = 43,560,000). Data is specified using time tracking, so the values for NSPDU and NFQDU are not used. The item DSSFL is used when data is stored in a DSS database, and is left blank. Urban water demand is specified as a time series from October 1921 through September 2009, with one row for each month and one column for each model subregion. Urban water demand for water years 1922-1992 were derived from the CVGSM model (James M. Montgomery Consulting Engineers, 1990B; Taghavi and Najmus, 2000), and for water years 1993-2009 were developed by DWR staff. Urban water demands for the original CVGSM model were based on an indoor use factor of 140 gallons per capita per day and population data from the U.S. Census Bureau (James M. Montgomery Consulting Engineers, 1990B).

Table 10. River inflow locations.

ID	River Node	Description
1	205	Sacramento River
2	211	Cow Creek
3	220	Battle Creek
4	218	Cottonwood Creek
5	225	Paynes and Sevenmile Creek
6	233	Antelope Creek Group
7	243	Mill Creek
8	237	Elder Creek
9	248	Thomes Creek
10	256	Deer Creek Group
11	263	Stony Creek
12	269	Big Chico Creek
13	283	Butte and Chico Creek
14	341	Feather River
15	349	Yuba River
16	357	Bear River
17	390	Cache Creek
18	374	American River
19	400	Putah Creek
20	188	Consumnes River
21	182	Dry Creek
22	173	Mokelumne River
23	161	Calaveras River
24	146	Stanislaus River
25	135	Tuolumne River
26	128	Oristimba Creek
27	116	Merced River
28	105	Bear Creek Group
29	93	Deadman's Creek
30	80	Chowchilla River
31	69	Fresno River
32	54	San Joaquin River
33	23	Kings River
34	420	Kaweah River
35	10	Tule River
36	1	Kern River
37	24	Friant-Kern Canal Wasteway deliveries to Kings River
38	11	Friant-Kern Canal Wasteway deliveries to Tule River
39	421	Friant-Kern Canal Wasteway deliveries to Kaweah River
40	4	Cross-Valley Canal spills to Kern River
41	4	Friant-Kern Canal spills to Kern River

River Inflow Data File

The Simulation River Inflow Data File CVinflows.dat contains surface water inflows at specified river nodes. C2VSim has inflow data for 41 river nodes (NCOLSTRM = 41). Inflow values are specified in thousands of acre-feet per month, and converted to simulation length units of cubic feet per month using a conversion factor (FACTSTRM = 43,560,000). Data is specified using time tracking, so the values for NSPSTRM and NFQSTRM are not used. The item DSSFL is used only when data is stored in a DSS database, and is left blank. The next section of the file lists the river nodes where inflow occurs; comments to the right identify the river reach. River inflow values are specified for each month from October 1921 through September 2009. 36 inflow values are at the points where a river crosses the model boundary, and five inflow values are canal spills to river channels. The river network and inflow locations are shown in figure 8, the river inflow locations are listed in table 10. River inflow data are listed in the report *Historical Rim Inflows for the California Central Valley Groundwater-Surface Water Simulation Model*.

Crop Demand Data File

The Simulation Crop Demand Data File CVcropdem.dat contains the minimum soil moisture requirements and crop irrigation efficiency for each agricultural crop. Time tracking is used, so the values of NSPDAG and NFDAG are ignored. The item DSSFL is used when data is stored in a DSS database, so it is left. Times are listed as year 4000, a flag that indicates the year is to be ignored and only the month and day are to be used to assign data values to time steps, allowing the values to be repeated for each year. For each calendar month, data are specified with two rows per subregion, the first containing the minimum soil moisture requirement and the second containing the crop efficiency, with one column for each agricultural crop and the last for bare soil. Minimum soil moisture is specified as a fraction of field capacity. Crop irrigation efficiency is specified as 0 for months in which the crop is not irrigated. Minimum soil moisture requirement and crop irrigation efficiency values were based on values used in the CVGSM model, which in turn were derived from the DWR Consumptive Use Model (James M. Montgomery Consulting Engineers, 1990B). Minimum soil moisture requirement values are listed in Addendum A.7, and crop irrigation efficiency values are listed in Addendum A.8.

Pumping Specification Data File

The Simulation Pumping Specification Data File CVPuSp.dat contains specification data for well pumping and element pumping. In C2VSim, well pumping is used to meet urban water demands and elemental pumping is used to meet agricultural pumping demands. The first section of the file has the number of model elements used for pumping (NSINK), and a flag controlling how pumped water is allocated (IOPT, one value for each column of the Pumping Data File). In C2VSim, groundwater pumping is simulated at all model elements (NSINK = 1392). Within each subregion, elemental pumping is distributed in proportion to the product of the pumping fraction (listed in the Elemental Pumping Specifications section) and the agricultural area within each element (IOPT = 3, listed 21 times, once for each column of the Pumping Data File).

The Well Pumping Specifications section contains information linking the pumping data file to the wells listed in the Preprocessor Well Specification File. There are 133 rows, each containing the data column (ICOLWL) from the pumping data file (CVpump.dat), irrigation fraction column (ICFIRIGWL) from the irrigation fraction file (CVIrFr.dat), proportion of the data column applied to this well (FRACWL), the model subregion the water is routed to (IRGWL), supply adjustment column (ICADJWL) from the supply adjustment file (CVsupplyadj.dat), maximum pumping data column (ICWLMAX) from the pumping data file (CVpump.dat), and fraction of the maximum pumping applied to this well (FWLMAX).

The Elemental Pumping Specifications section contains one row for each model element. The first item in each row is the element number (ID), followed by the column in the Pumping Data File (CVpump.dat) that contains pumping data for this element (ICOLSK), and the column in the Irrigation Fractions Data file (CVIrFr.dat) that specifies the proportion of groundwater used for agricultural purposes (FRACSK). Next, the relative proportion of pumping from the pumping data file assigned to the element (FRACSK) and the allocation to model layers within this element (FRACSKL, one column for each model layer) are listed. The next column lists the model subregion the water is delivered to (IRGSK); a value of -1 indicates the water is delivered to the element it is pumped from, a positive number indicates it is delivered to the indicated subregion, and 0 indicates the water is exported outside the model domain. The last three columns contain the column of the Supply Adjustment Specification File (CVsupplyadj.dat) containing the supply adjustment specification (ICADJSK), the column in the Pumping Data File (CVpump.dat) containing the maximum pumping amount ICSKMAX (equal to the actual pumping amount, or ICOLSK) and the fraction of ICSKMAX to be used as the minimum pumping amount (FSKMAX, set to 1).

Pumping Data File

The Simulation Pumping Data File CVpump.dat contains pumping rates for the wells and elements specified in the Pumping Specifications File (CVPuSp.dat). Monthly agricultural pumping rates for each of 21 model subregions are listed, followed by monthly urban pumping rates for each of 21 model subregions (NCOLPUMP = 42). Pumping rates are specified in units of thousand acre-feet per month, and are converted to simulation units of cubic feet per month using a conversion factor (FACTPUMP = 43,560,000). Data is specified using time tracking, so the values for NSPPUMP and NFQPUMP are not used. The item DSSFL is used when data is stored in a DSS database, and is left blank.

The Pumping Data Section contains groundwater pumping rates for each simulation time step. The values in the file CVpump.dat are estimated groundwater pumping rates for each month from October 1921 through September 2009. Groundwater pumping is not regulated or recorded in California's Central Valley, and no reliable long-term data on local groundwater pumping rates throughout the Central Valley are available. The groundwater pumping rates in the Pumping Data File CVpump.dat were estimated by IWFM as a closure term to match water supplies to water demands in each model subregion. The Simulation program can be run with pumping adjustment on (KOPTV = "01" in CVSim.in) to estimate groundwater pumping for each subregion as the difference between applied surface water and calculated water demands. Agricultural and urban pumping rates from the IWFM Land and Water use budget can then be saved in the Pumping Data File and used as input values for subsequent model runs. This is how the values in file CVpump.dat were derived.

Surface Water Diversion Specification File

The Simulation Surface Water Diversion Specification File CVdivspec.dat contains data specifying the locations, properties and recharge zones for surface water diversions and bypasses. The Surface Water Diversion Specification File contains four sections: a surface water diversion specifications section listing the river nodes where surface water diversions occur; a surface water diversion recharge specifications section listing model elements receiving recoverable losses (recharge); a surface water bypass specifications listing the river nodes where surface-water bypasses begin and end; and a bypass recharge specifications section listing the model elements receiving bypass recoverable losses. C2VSim has 246 surface water diversions and 12 bypasses (figure 8 and tables 11 and 12).

Diversions

The surface water diversion specifications section begins with the number of diversions (NRDV = 246). There is then one row for each surface water diversion, listed in increasing numerical order. Each row begins with the surface water diversion identification number (ID). The source river node (IRDV) is next, indicating the number of the river node the diversion is taken from, or 0 for surface water

Table 11. Surface water diversion specification data.

ID	Data Column	Source Node	Destination Subregion	Use	Description
1	1	Import	1	Ag	Whiskeytown and Shasta for Ag
2	2	Import	1	M&I	Whiskeytown and Shasta for M&I
3	3	206	1	Ag	Sacramento River to Bella Vista conduit for Ag
4	4	206	1	M&I	Sacramento River to Bella Vista conduit for M&I
5	5	207	Export	-	Sacramento River to Bella Vista conduit for export
6	6	216	1	Ag	Sacramento River, Keswick Dam to Red Bluff, for Ag
7	7	206	1	M&I	Sacramento River, Keswick Dam to Red Bluff, for M&I
8	8	212	1	Ag	Cow Creek riparian diversions
9	9	221	1	Ag	Battle Creek riparian diversions
10	10	Import	1	Ag	Cottonwood Creek riparian diversions
11	11	Import	2	Ag	Clear Creek riparian diversions
12	12	231	2	Ag	Sacramento River diversions to the Corning Canal
13	13	264	2	Ag	Stony Creek to North Canal
14	14	Import	2	Ag	Stony Creek to South Canal
15	15	264	3	Ag	Stony Creek to the Tehama-Colusa Canal
16	16	264	3	Ag	Stony Creek to the Glenn-Colusa Canal
17	17	262	2	Ag	Sacramento River to Subregion 2
18	18	234	2	Ag	Antelope Creek riparian diversions
19	19	245	2	Ag	Mill Creek riparian diversions
20	20	242	2	Ag	Elder Creek riparian diversions
21	21	253	2	Ag	Thomes Creek riparian diversions
22	22	258	2	Ag	Deer Creek riparian diversions
23	23	231	2	Ag	Sacramento River to the Tehama-Colusa Canal to Subregion 2
24	24	231	3	Ag	Sacramento River to the Tehama-Colusa Canal to Subregion 3
25	25	261	3	Ag	Sacramento River to the Glenn-Colusa Canal for Ag
26	26	261	3	Refuge	Sacramento River to the Glenn-Colusa Canal for Refuges
27	27	282	3	Ag	Sacramento River to Subregion 3
28	28	331	4	Ag	Sacramento River to Subregion 4
29	29	Import	5	Ag	Little Chico Creek
30	30	Import	5	Ag	Tarr Ditch
31	31	Import	5	Ag	Miocine and Wilenor Canals
32	32	Import	5	M&I	Palermo Canal
33	33	Import	5	Ag	Oroville-Wyandotte ID through Forbestown Ditch
34	34	Import	5	Ag	Little Dry Creek
35	35	Import	5	Ag	Bangor Canal
36	36	Import	5	Ag	Thermalito Afterbay
37	37	347	5	Ag	Feather River to Subregion 5 for Ag (replaced by Thermalito Afterbay)
38	38	Import	5	M&I	Feather River to Thermalito ID
39	39	347	5	Ag	Feather River to Subregion 5 for Ag
40	40	352	5	M&I	Feather River to Yuba City
41	41	364	7	Ag	Feather River to Subregion 7 for Ag
42	42	351	5	Ag	Yuba River for Ag
43	43	351	5	M&I	Yuba River for M&I

ID	Data Column	Source Node	Destination Subregion	Use	Description
44	44	358	5	Ag	Bear River to Camp Far West ID North Side
45	45	358	7	Ag	Bear River to Camp Far West ID South Side
46	46	358	7	Ag	Bear River to South Sutter WD
47	47	Import	7	Ag	Bear River Canal to South Sutter WD
48	48	Import	7	Ag	Boardman Canal
49	49	Import	7	Ag	Combie (Gold Hill) Canal
50	50	Import	7	Ag	Cross Canal
51	51	284	5	Ag	Butte Creek at Parrott-Phelan Dam
52	52	286	5	Ag	Butte Creek at Durham Mutual Dam
53	53	287	5	Ag	Butte Creek at Adams & Gorrill Dams
54	54	285	4	Ag	Butte Creek to RD 1004
55	55	291	5	Refuge	Butte Creek to Sutter and Butte Duck Clubs
56	56	292	4	Ag	Butte Slough
57	57	335	4	Refuge	Sutter Bypass East Borrow Pit to Sutter NWR
58	58	336	4	Ag	Sutter Bypass West Borrow Pit North of Tisdale Bypass
59	59	337	4	Ag	Sutter Bypass East Borrow Pit to lands within Sutter Bypass
60	60	337	4	Ag	Sutter Bypass East Borrow Pit from North of Wadsworth Canal to Gilsizer Slough
61	61	339	5	Ag	Sutter Bypass East Borrow Pit South of Gilsizer Slough to
62	62	327	3	Ag	Colusa Basin Drain to Subregion 3 for Ag
63	63	324	3	Refuge	Colusa Basin Drain to Subregion 3 for Refuges
64	64	329	6	Ag	Knights Landing Ridge Cut
65	65	371	6	Ag	Sacramento River between Knights Landing and Sacramento to Subregion 6 for Ag
66	66	381	6	M&I	Sacramento River to City of West Sacramento
67	67	372	7	Ag	Sacramento River between Knights Landing and Sacramento to Subregion 7 for Ag
68	68	381	8	M&I	Sacramento River to City of Sacramento
69	69	Import	6	Ag	Cache Creek
70	70	398	6	Ag	Yolo Bypass
71	71	400	6	Ag	Putah South Canal for Ag
72	72	400	6	M&I	Putah South Canal for M&I
73	73	400	Export	-	Putah South Canal exports
74	74	404	6	Ag	Putah Creek riparian diversions
75	75	Import	7	Ag	Folsom Lake for Ag
76	76	Import	7	M&I	Folsom Lake for M&I
77	77	375	8	Ag	Folsom South Canal for Ag
78	78	375	8	M&I	Folsom South Canal for M&I
79	79	375	Export	-	Folsom South Canal exports
80	80	377	7	M&I	American River to Carmichael WD
81	81	378	7	M&I	American River to City of Sacramento
82	82	193	8	Ag	Cosumnes River
83	83	Import	8	Ag	Mokelumne River from Comanche Reservoir
84	84	195	8	Ag	Mokelumne River
85	85	165	8	Ag	Calaveras River
86	86	418	9	Ag	Sacramento-San Joaquin Delta for Ag

ID	Data Column	Source Node	Destination Subregion	Use	Description
87	87	418	9	M&I	Sacramento-San Joaquin Delta for M&I
88	88	413	6	Ag	Sacramento-San Joaquin Delta to North Bay Aqueduct for Ag
89	89	413	6	M&I	Sacramento-San Joaquin Delta to North Bay Aqueduct for M&I
90	90	413	Export	-	Sacramento-San Joaquin Delta to North Bay Aqueduct export
91	91	418	Export	-	Sacramento-San Joaquin Delta to Contra Costa Canal
92	92	418	Export	-	Sacramento-San Joaquin Delta to CVP
93	93	418	Export	-	Sacramento-San Joaquin Delta to SWP
94	94	147	11	Ag	Stanislaus River to South San Joaquin Canal for Ag
95	95	147	11	M&I	Stanislaus River to South San Joaquin Canal for M&I
96	96	147	11	Ag	Stanislaus River to Oakdale Canal for Ag
97	97	147	11	M&I	Stanislaus River to Oakdale Canal for M&I
98	98	152	11	Ag	Stanislaus River riparian for Ag
99	99	152	11	M&I	Stanislaus River riparian for M&I
100	100	136	Export	-	Tuolumne River to Modesto Canal
101	101	Import	11	Ag	Modesto Canal for Ag
102	102	Import	11	M&I	Modesto Canal for M&I
103	103	142	11	Ag	Tuolumne River right bank riparian diversions for Ag
104	104	142	11	M&I	Tuolumne River right bank riparian diversions for M&I
105	105	142	12	Ag	Tuolumne River left bank riparian diversions for Ag
106	106	142	12	M&I	Tuolumne River left bank riparian diversions for M&I
107	107	136	Export	-	Tuolumne River to Turlock Canal
108	108	Import	12	Ag	Turlock Canal for Ag
109	109	Import	12	M&I	Turlock Canal for M&I
110	110	117	12	Ag	Merced River to Merced ID Northside Canal for Ag
111	111	117	12	M&I	Merced River to Merced ID Northside Canal for M&I
112	112	123	12	Ag	Merced River right bank riparian diversions for Ag
113	113	123	12	M&I	Merced River right bank riparian diversions for M&I
114	114	123	13	Ag	Merced River left bank riparian diversions for Ag
115	115	123	13	M&I	Merced River left bank riparian diversions for M&I
116	116	117	13	Ag	Merced River to Merced ID Main Canal for Ag
117	117	117	13	M&I	Merced River to Merced ID Main Canal for M&I
118	118	81	13	Ag	Chowchilla River to Chowchilla WD
119	119	81	13	Ag	Chowchilla River riparian diversions for Ag
120	120	81	13	Spreading	Chowchilla River diversions for Spreading
121	121	70	13	Ag	Fresno River to Madera ID
122	122	70	13	Ag	Fresno River riparian diversions for Ag
123	123	70	13	Spreading	Fresno River diversions for Spreading
124	124	60	13	Ag	San Joaquin River riparian diversions, Friant to Gravelly Ford, to Subregion 13 for Ag
125	125	60	13	M&I	San Joaquin River riparian diversions, Friant to Gravelly Ford, to Subregion 13 for M&I
126	126	60	16	Ag	San Joaquin River riparian diversions, Friant to Gravelly Ford, to Subregion 16 for Ag
127	127	60	16	M&I	San Joaquin River riparian diversions, Friant to Gravelly Ford, to Subregion 16 for M&I

ID	Data Column	Source Node	Destination Subregion	Use	Description
128	128	145	10	Ag	San Joaquin River riparian diversions, Fremont Ford to Vernalis, to Subregion 10 for Ag
129	129	145	11	Ag	San Joaquin River riparian diversions, Fremont Ford to Vernalis, to Subregion 11 for Ag
130	130	134	12	Ag	San Joaquin River riparian diversions, Fremont Ford to Vernalis, to Subregion 12 for Ag
131	131	115	13	Ag	San Joaquin River riparian diversions, Fremont Ford to Vernalis, to Subregion 13 for Ag
132	132	24	16	Ag	Kings River to Fresno ID for Ag
133	133	24	16	Spreading	Kings River to Fresno ID for Spreading
134	134	25	17	Ag	Kings River to Consolidated ID for Ag
135	135	25	17	Spreading	Kings River to Consolidated ID for Spreading
136	136	25	17	Ag	Kings River to Alta ID for Ag
137	137	25	17	Spreading	Kings River to Alta ID for Spreading
138	138	28	15	Ag	Kings River Main Stem for Ag
139	139	28	15	Spreading	Kings River Main Stem for Spreading
140	140	43	15	Ag	Kings River North Fork for Ag
141	141	43	15	Spreading	Kings River North Fork for Spreading
142	142	37	15	Ag	Kings River South Fork for Ag
143	143	37	15	Spreading	Kings River South Fork for Spreading
144	144	52	15	Ag	Kings River Fresno Slough for Ag
145	145	52	15	Spreading	Kings River Fresno Slough for Spreading
146	146	420	18	Ag	Kaweah River Partition A for Ag
147	147	420	18	Spreading	Kaweah River Partition A for Spreading
148	148	422	18	Ag	Kaweah River Partition B for Ag
149	149	422	18	Spreading	Kaweah River Partition B for Spreading
150	150	422	18	Ag	Kaweah River Partition C for Ag
151	151	422	18	Spreading	Kaweah River Partition C for Spreading
152	152	420	18	Ag	Kaweah River Partition D for Ag
153	153	420	18	Spreading	Kaweah River Partition D for Spreading
154	154	426	18	Ag	Kaweah River to Corcoran ID for Ag
155	155	426	18	Spreading	Kaweah River to Corcoran ID for Spreading
156	156	18	18	Ag	Tule River for Ag
157	157	18	18	Spreading	Tule River for Spreading
158	158	7	19	Ag	Kern River to Subregion 19 for Ag
159	159	7	19	Spreading	Kern River to Subregion 19 for Spreading
160	160	2	20	Ag	Kern River to Subregion 20 for Ag
161	161	2	20	M&I	Kern River to Subregion 20 for M&I
162	162	2	20	Spreading	Kern River to Subregion 20 for Spreading
163	163	2	21	Ag	Kern River at Rocky Point Weir for Ag
164	164	2	21	M&I	Kern River at Rocky Point Weir for M&I
165	165	3	21	Ag	Kern River at Calloway River Weir for Ag
166	166	3	21	M&I	Kern River at Calloway River Weir for M&I
167	167	3	21	Spreading	Kern River at Calloway River Weir for Spreading
168	168	4	21	Ag	Kern River at River Canal Weir for Ag
169	169	4	21	M&I	Kern River at River Canal Weir for M&I

ID	Data Column	Source Node	Destination Subregion	Use	Description
170	170	4	21	Spreading	Kern River at River Canal Weir for Spreading
171	171	Import	9	Ag	Delta Mendota Canal to Subregion 9 for Ag
172	172	Import	10	Ag	Delta Mendota Canal to Subregion 10 for Ag
173	173	Import	10	M&I	Delta Mendota Canal to Subregion 10 for M&I
174	174	Import	10	Refuge	Delta Mendota Canal to Subregion 10 for Refuges
175	175	Import	13	Ag	Delta Mendota Canal to Subregion 13 for Ag
176	176	Import	-	Seepage	Delta Mendota Canal seepage
177	177	Import	10	Ag	Mendota Pool to Subregion 10 for Ag
178	178	Import	10	Refuge	Mendota Pool to Subregion 10 for Refuges
179	179	Import	13	Ag	Mendota Pool to Subregion 13 for Ag
180	180	Import	14	Ag	Mendota Pool to Subregion 14 for Ag
181	181	Import	15	Ag	Mendota Pool to Subregion 15 for Ag
182	182	Import	15	M&I	Mendota Pool to Subregion 15 for M&I
183	183	Import	15	Refuge	Mendota Pool to Subregion 15 for Refuges
184	184	Import	10	Ag	O'Neill Forebay for Ag
185	185	Import	10	M&I	O'Neill Forebay for M&I
186	186	Import	10	Refuge	O'Neill Forebay for Refuges
187	187	Import	10	Ag	San Luis Canal to Subregion 10 for Ag
188	188	Import	10	M&I	San Luis Canal to Subregion 10 for M&I
189	189	Import	10	Refuge	San Luis Canal to Subregion 10 for Refuges
190	190	Import	14	Ag	San Luis Canal to Subregion 14 for Ag
191	191	Import	14	M&I	San Luis Canal to Subregion 14 for M&I
192	192	Import	14	Refuge	San Luis Canal to Subregion 14 for Refuges
193	193	Import	15	Ag	San Luis Canal to Subregion 15 for Ag
194	194	Import	15	M&I	San Luis Canal to Subregion 15 for M&I
195	195	Import	15	Refuge	San Luis Canal to Subregion 15 for Refuges
196	196	Import	18	Ag	California Aqueduct to Subregion 18 for Ag
197	197	Import	19	Ag	California Aqueduct to Subregion 19 for Ag
198	198	Import	19	Spreading	California Aqueduct to Subregion 19 for Spreading
199	199	Import	19	M&I	California Aqueduct to Subregion 19 for M&I
200	200	Import	19	Refuge	California Aqueduct to Subregion 19 for Refuges
201	201	Import	20	Ag	California Aqueduct to Subregion 20 for Ag
202	202	Import	21	Ag	California Aqueduct to Subregion 21 for Ag
203	203	Import	21	Spreading	California Aqueduct to Subregion 21 for Spreading
204	204	Import	21	M&I	California Aqueduct to Subregion 21 for M&I
205	205	Import	10	Seepage	San Luis Canal seepage losses, Subregion 10
206	206	Import	14	Seepage	San Luis Canal seepage losses, Subregion 14
207	207	Import	15	Seepage	San Luis Canal seepage losses, Subregion 15
208	208	Import	19	Seepage	California Aqueduct seepage losses, Subregion 19
209	209	Import	21	Seepage	California Aqueduct seepage losses, Subregion 21
210	210	Import	13	Ag	Madera Canal for Ag
211	211	Import	13	M&I	Madera Canal for M&I
212	212	Import	15	Ag	Friant-Kern Canal to Subregion 15

ID	Data Column	Source Node	Destination Subregion	Use	Description
213	213	Import	16	Ag	Friant-Kern Canal to Subregion 16 for Ag
214	214	Import	16	Spreading	Friant-Kern Canal to Subregion 16 for Spreading
215	215	Import	16	M&I	Friant-Kern Canal to Subregion 16 for M&I
216	216	Import	17	Ag	Friant-Kern Canal to Subregion 17 for Ag
217	217	Import	17	Spreading	Friant-Kern Canal to Subregion 17 for Spreading
218	218	Import	17	M&I	Friant-Kern Canal to Subregion 17 for M&I
219	219	Import	18	Ag	Friant-Kern Canal to Subregion 18 for Ag
220	220	Import	18	Spreading	Friant-Kern Canal to Subregion 18 for Spreading
221	221	Import	18	M&I	Friant-Kern Canal to Subregion 18 for M&I
222	222	Import	19	Ag	Friant-Kern Canal to Subregion 19 for Ag
223	223	Import	19	Spreading	Friant-Kern Canal to Subregion 19 for Spreading
224	224	Import	19	Refuge	Friant-Kern Canal to Subregion 19 for Refuges
225	225	Import	20	Ag	Friant-Kern Canal to Subregion 20 for Ag
226	226	Import	20	Spreading	Friant-Kern Canal to Subregion 20 for Spreading
227	227	Import	20	M&I	Friant-Kern Canal to Subregion 20 for M&I
228	228	Import	21	Ag	Friant-Kern Canal to Subregion 21 for Ag
229	229	Import	21	Spreading	Friant-Kern Canal to Subregion 21 for Spreading
230	230	Import	21	M&I	Friant-Kern Canal to Subregion 21 for M&I
231	231	Import	16	Seepage	Friant-Kern Canal seepage losses, Subregion 16
232	232	Import	17	Seepage	Friant-Kern Canal seepage losses, Subregion 17
233	233	Import	18	Seepage	Friant-Kern Canal seepage losses, Subregion 18
234	234	Import	20	Seepage	Friant-Kern Canal seepage losses, Subregion 20
235	235	Import	21	Seepage	Friant-Kern Canal seepage losses, Subregion 21
236	236	Import	17	Ag	Cross-Valley Canal Subregion 17
237	237	Import	18	Ag	Cross-Valley Canal to Subregion 18 for Ag
238	238	Import	18	M&I	Cross-Valley Canal to Subregion 18 for M&I
239	239	Import	19	Refuge	Cross-Valley Canal to Subregion 19 for Refuges
240	240	Import	20	Ag	Cross-Valley Canal to Subregion 20 for Ag
241	241	Import	20	Spreading	Cross-Valley Canal to Subregion 20 for Spreading
242	242	Import	21	Ag	Cross-Valley Canal to Subregion 21 for Ag
243	243	Import	21	Spreading	Cross-Valley Canal to Subregion 21 for Spreading
244	244	24	Export	-	Kings River diversions to Friant-Kern Canal
245	245	421	Export	-	Kaweah River diversions to Friant-Kern Canal
246	246	12	Export	-	Tule River diversions to Friant-Kern Canal

imports. The maximum diversion amount (ICDVMAX) indicates the appropriate column of the Surface Water Diversion Data File CVdiversions.dat, followed by the fraction of the amount in this column to be used as the maximum diversion amount (FDVMAX); these are set to ICDVMAX = 260 and FDVMAX = 1.0.

The next four columns of the surface water diversion specifications section list the column of the Surface Water Diversion Data File containing the recoverable loss (ICOLRL) and the fraction of this amount to be used as the recoverable loss (FRACRL), followed by the column of the Surface Water Diversion Data File containing the non-recoverable loss (ICOLNL) and the fraction of this amount to be used as the non-recoverable loss (FRACNL). The next columns specify how the surface water diversion is allocated to model subregions: the first item indicates the number of subregions the diversion is apportioned to (NDLDV = 1 for all surface water diversions), then for each recipient subregion the subregion number is specified (IRGDL), followed by the data column of the Surface Water Diversion Data File (ICOLDL), the relative proportion of the data value apportioned to the subregion (FRACDL), the fraction used for agricultural purposes (ICFSIRIG), and the supply adjustment specification (ICADJ). For most surface water diversions, a single surface water diversion value is allocated to deliveries, recoverable losses and non-recoverable losses, such that FRACDL + FRACRL + FRACNL = 1.0. Several surface water diversions have a separate time series for recoverable losses, and this is reflected in the values of FRACDL and FRACRL. The Surface Water Diversion Data File, CVdiversion.dat, includes comment lines above each diversion specification line describing the diversion.

Diversion Recoverable Loss Zones

The next section of the Surface Water Diversion Specification File lists the zone, or group of elements, receiving recoverable losses as groundwater recharge for each surface water diversion. In C2VSim, these zones correspond roughly to the area underlying the canals conveying the diverted water and thus receiving canal leakage. The first line of each diversion recharge zone specification begins with the diversion number (ID), followed by the total number of elements in the recharge zone (NERELS). There are then NERELS rows, each listing an element number (IERELS) and the relative proportion of the recoverable loss to be applied to the element as recharge at the water table (FERELS). The IWFM Simulation program adds up the FERELS values for each surface water diversion, and then apportions the recoverable loss as (FERELS(i)/sum(FERELS) to each element (i) accordingly. If IERELS = 0 and FERELS = 0, then all recoverable losses are exported from the model. Recoverable losses are applied directly at the water table in each time step.

Bypass Specification

Bypasses divert surface water from one river node to another river node or lake. Bypass rates can be specified using either a time series or a rating table. The bypass specification section begins with the number of bypasses (NDIVS = 12). This is

Table 12. Surface water bypasses.

ID	Data Column	Source Node	Destination Node	Description
1	248	280	290	Moulton Weir spill to Butte Basin
2	249	282	291	Colusa Weir spill to Butte Basin
3	250	297	337	Tisdale Weir near Grimes
4	251	367	396	Freemont Weir spill to Yolo Bypass
5	252	372	397	Sacramento Weir spill to Yolo Bypass
6	253	329	396	Knights Landing Ridge Cut flood flow to Yolo Bypass
7	T	32	40	Kings River Bifurcation at Army Weir, flow to Fresno Slough
8	T	428	Recharge	Kaweah River to Kaweah River Fan (spreading)
9	T	18	Recharge	Tule River to Tule River Fan (spreading)
10	T	449	Recharge	Kings River Flood Channel to basin (spreading)
11	T	39	Recharge	South Fork of Kings River to basin (spreading)
12	258	8	Lake 1	Kern River to Buena Vista Lake

followed by four rating-table conversion factors that convert the spatial (FACTX) and temporal (TUNITX) components of river flow, and the spatial (FACTY) and temporal (TUNITY) components of the diversion amount. In C2VSim, bypass rating tables are in units of ft3/sec, and are converted to cubic feet per minute (FACTX = FACTY = 60), with the time unit specified as one minute (TUNITX = TUNITY = '1min').

The bypass specification section contains one line for each bypass. There are two specification formats, depending on whether the bypass flows are specified using a time series or using a rating table. The first three items are the same for both specification types, beginning with the bypass number (ID), followed by the source river node (IA > 0) followed by the destination river node (IDIVT > 0). The next number (IDIVC) indicates how bypass flow values are specified: if IDIVC is positive, it specifies the column in the Surface Water Diversion Data File CVdiversions.dat; if it is negative, it specifies the number of points in the diversion rating table. All bypass diversion rating tables in this file must have the same number of points; four points are used in diversion rating tables in C2VSim. The next two numbers indicate the fraction of bypass flow assigned as recoverable losses (DIVRL) and non-recoverable losses (DIVNL). If a rating table is used, |IDIVC| (the absolute value of IDIVC) additional lines are used to list the river flow rate (DIVX) and corresponding bypass flow rate (DIVY) for |IDIVC| flow rate pairs. These flow values are entered in units of ft3/sec, and the multipliers FACTX, TUNITX, FACTY and TUNITY convert these to units of ft3/min; the time-tracking capability of IWFM further converts these to the internal units used in the simulation.

Bypass Recoverable Loss Zones

The final section of the Surface Water Diversion Specification File lists recharge locations for bypass recoverable losses. The bypass number (ID) is listed, followed by the number of elements receiving recharge (NERELS), and then NERELS pairs of data indicating individual element numbers (IERELS) and the relative proportion of the recoverable loss applied to the element (FERELS). If NERELS is negative, then the absolute value |NERELS| specifies the ID number of the lake receiving recoverable losses. If NERELS is zero, then recoverable losses are exported from the model.

Bypasses #1 through #5
The first five bypasses in C2VSim simulate (1) the Moulton Weir, (2) the Colusa Weir, (3) the Tisdale Weir, (4) the Fremont Weir, and (5) the Sacramento Weir, components of the Sacramento River Flood Control System. These bypasses divert floodwaters from the Sacramento River into parallel flow channels, the Butte Basin and Sutter Bypass and the Yolo Bypass. The Moulton, Colusa, Tisdale and Fremont weirs are gravity structures, which allow floodwaters to pass once the river stage exceeds the weir elevation. The Sacramento Weir has gages above the overflow section that allow the bypass flow rate to be regulated.

The Moulton Weir, with a design maximum capacity of 25,000 cfs, is located on the left (east) bank of the Sacramento River approximately eight miles north of Colusa and routes flood waters to the Butte Basin. The Colusa Weir, with a design capacity of 70,000 cfs is located one mile north of Colusa along the left bank of the Sacramento River, and routes flood waters to the Butte Basin. The Tisdale Weir, with a maximum design capacity of 38,000 cfs, is located along the left side of the Sacramento River between Colusa and Grimes, and routes flood waters into the four-mile-long Tisdale Bypass which discharges to the Sutter Bypass. The Butte Basin drains into the Sutter Bypass, which drains into the Feather River a few miles upstream from the confluence of the Feather and Sacramento rivers.

The Fremont Weir, with a design capacity of 343,000 cfs, is located on the right bank of the Sacramento River about 15 miles northwest of Sacramento and eight miles northeast of Woodland. The Fremont Weir releases flood waters from the Sacramento River, Sutter Bypass and Feather River to the Yolo Bypass. The Sacramento Weir, with a design capacity of 112,000 cfs, is located on the right bank of the Sacramento River approximately two miles upstream of its confluence with the American River, and routes Sacramento River and American River flood waters down the one-mile-long Sacramento Bypass to the Yolo Bypass. The Yolo Bypass rejoins the Sacramento River a few miles upstream of Rio Vista.

Bypass #6, the Knights Landing Ridge Cut
The Knights Landing Ridge Cut carries water from the Colusa Basin Drain (which flows to the Sacramento River) to the Tule Canal in the Yolo Bypass. The Knights Landing Ridge Cut is not simulated as a river reach within C2VSim. The bypass routes water from the Colusa Basin Drain to the Tule Canal.

Bypass #7, the Kings River Bifurcation
The Kings River channel divides into two channels near the San Joaquin Valley trough. One channel, called the North Fork, flows northwest to Fresno Slough, the James Bypass, the Mendota Pool, and eventually enters the San Joaquin River near Firebaugh. The other channel, called the South Fork, flows south to discharge into Tulare Lake. The Kings River naturally flows to the North Fork, and water is diverted to the South Fork to satisfy divrsions.

Bypasses #8-11, Artificial Recharge
Three bypasses use the IWFM Simulation program's bypass recharge functionality to simulate distal fan recharge on the (8) Kaweah River, (9) Tule River, (10) Kern River Flood Channel and (11) South Fork of the Kings River. A bypass is specified to divert all water reaching the end of each river. The recoverable loss fraction for each of these bypasses is set to 100%, so all of the water that reaches the end of the river is applied as recharge to the recharge zone associated with the bypass. The purpose of this is two-fold: to simulate artificial recharge that is believed to occur along these rivers, and to reduce flows to Tulare Lake. (Bypass 11 is not active.)

Bypass #12, Kern River to Buena Vista Lake
A bifurcation at the end of the Kern River allows water to be diverted to either Buena Vista Lake or the Kern River Flood Channel. Within C2VSim, water reaching the end of the Kern River is routed to the Kern River Flood Channel, and a bypass is used to simulate flows to Buena Vista Lake. This is simulated with a time series, which is provisionally set to zero for all time steps owing to a lack of data.

Surface Water Diversion Data

The Simulation Surface Water Diversion Data File CVdiversions.dat contains time-series surface water diversion and bypass flow rates for river nodes specified in the Surface Water Diversion Specification File. The first item in this file is NCOLDV, the number of data columns used; NCOLDV = 265 for C2VSim. Diversion and bypass rates are specified in units of thousand acre-feet per month, and converted to simulation length units at runtime using the flow rate conversion factor (FACTDV = 43,560,000). Data is specified using time tracking, so the values for NSPDV and NFQDV are not used. The item DSSFL is used when data is stored in a DSS database, so it is left blank.

Diversion and bypass flow rates are specified for each month from October 1921 through September 2009 using the IWFM time-tracking capability. The first 246 columns hold flow rates for individual surface water diversions and in some cases for associated recoverable losses, columns 247 to 250 are not used, columns 251 to 261 hold bypass flow rates, columns 262 to 264 are not used, and column 265 holds a diversion adjustment control flag set to "-99.00". A comment section preceding the data lists the diversion or bypass associated with each data column. Surface water diversion and bypass flows are listed in the companion report Historical Rim Infolws, Surface Water Diversions and Bypass Flows.

Irrigation Fraction Data File

The Simulation Irrigation Fraction Data File CVIrFr.dat contains time-series data specifying the fraction of surface water and groundwater to be used for agricultural purposes, with the remainder allocated to urban usage. Individual columns in this file are associated with surface water diversions in the Surface Water Diversion Specification File and with groundwater pumping in the Pumping Specification File. The first data line lists the number of data columns in the Irrigation Fractions File; NCOLIRF = 23. Data is specified using time tracking, so the values for NSPIRF and NFQIRF are not used (NSPIRF = 1, NFQIRF = 1). The item DSSFL is used when data is stored in a DSS database, and is left blank.

A single irrigation fraction data set is entered for year 2100, and thus acts as a constant value for the entire model simulation period. Data in columns 1 to 21 (elemental groundwater pumping for each model subregion) and column 23 (agricultural surface water diversions), is set to 1.00, indicating that all water is used to meet agricultural water demands. Data in column 22 (specified wells and urban surface water diversions) is set to 0.00, indicating all water is used to satisfy urban water demands.

Maximum Lake Elevation Data File

The Simulation Maximum Lake Elevation Data File CVmaxlake.dat contains time-series data specifying maximum lake surface altitudes above datum for each simulated lake. The first data line lists the number of lakes NCOLHLMX. C2VSim simulates two lakes (NCOLHLMX = 2): Buena Vista Lake receives flood waters from the Kern River and discharges to the Kern River Flood Channel, and Tulare Lake receives water from the South Fork Kings, Kaweah, and Tule Rivers and the Kern River Flood Channel and discharges to the North Fork Kings River. Data is entered in units of feet, and converted to simulation units with a conversion factor (FACTHLMX = 1). Maximum lake elevations are specified using time tracking, so the values for NSPHLMX and NFQHLMX are not used. The item DSSFL is used only when data is stored in a DSS database, so it is left blank.

A single maximum lake elevation data set is entered for year 2100, and thus acts as a constant value for the entire model simulation period. Buena Vista Lake has rarely received water since the completion of the Lake Isabella reservoir in 1954. The maximum lake elevation for Buena Vista Lake is specified as 321 ft. Tulare Lake is situated south of the divide between the Tulare and San Joaquin basins. When the water level in Tulare Lake rises above 206 ft, the flow in the South Fork of the Kings River will reverse direction and the lake will drain to the North Fork Kings River, which flows to Fresno Slough, James Bypass and eventually to the San Joaquin River. Thus the maximum lake altitude for Tulare Lake is specified as 206 ft. IWFM does not allow river reaches to flow in two directions, so in C2VSim Tulare Lake

Table 13. Re-use fractions

Subregion	Re-use Fraction
1	0.000
2	0.000
3	0.559
4	0.535
5	0.527
6	0.393
7	0.392
8	0.275
9	0.274
10	0.163
11	0.287
12	0.304
13	0.310
14	0.214
15	0.168
16	0.299
17	0.294
18	0.328
19	0.191
20	0.316
21	0.176
Urban	0.000

** This data can be entered as a time series, but is constant in the C2VSIM model.

discharges flows to a river node on the North Fork Kings River downstream from the Kings River bifurcation. The use of bypasses and recharge zones to simulate aquifer storage programs that limit Tulare Lake inflow is detailed in the section above that describes the Surface Water Diversion Specification File.

Irrigation Water Re-use Factors File

The Simulation Irrigation Water Re-use Factors File CVruf.dat contains time-series factors specifying the portion of agricultural irrigation water that is recycled and reused within each model subregion and for urban areas. The first data item is the number of data columns, one greater than the number of subregions (NRUF = 22). Re-use factors are specified using time tracking, so the values for NSPRUF and NFQRUF are not used. The item DSSFL is used only when data is stored in a DSS database, and is left blank. A single re-use factor data set is entered for year 2100, and thus acts as a constant value for the entire simulation period. Irrigation water re-use factors used in C2VSim are listed in table 13.

Output files

The IWFM Simulation program produces DSS, binary, and ASCII text output files as specified in the Simulation Main Input File. Only those files specified in the Simulation Main Input File are created; if the name of an optional file is omitted, the file is not produced. The IWFM Simulation program can produce ten different ASCII output files; five of these are produced by C2VSim and are described in this section. The Simulation program can also produce nine binary output files, eight read by the Budget program and one is read by the Z-Budget program; these files are described in the Budget and Z-Budget sections below.

The standard Simulation output file SimulationMessages.out contains a record of the simulation progress, including a list of input files, nodal parameter values (if KDEB = 2 in the Simulation Main Input File), numerical convergence of each iteration for each time step, and the total execution time. Final simulation results are printed to the required file CVfinallist.out, which has the same format as the Initial Conditions File, allowing it to be used as an initial condition in future simulation exercises. The groundwater head at each model node for each time step is printed to the optional file CVGWheadall.out

Four hydrograph files can be specified in the Print Specification File CVprint.dat. The groundwater level hydrographs output file CVGWhyd.out contains time series groundwater hydrographs for each location for which x-y coordinates and model layers as specified by the user in the file CVprint.dat. The stream-flow hydrographs output file CVSWhyd.out contains time series surface water hydrographs for river nodes specified by the user in the file CVprint.dat. The tile drain output file CVtiledrn.out contains time series tile drain discharge hydrographs for locations specified in the file CVprint.dat. The subsidence output file CVSubsHyd.out contains time series subsidence hydrographs for locations specified in the file CVprint.dat.

The IWFM Simulation program can print two files that contain time series of nodal values for each model layer that are easily read by the graphical program TecplotTM (Tecplot, Inc. 2011). The file CVGWheadTecPlot.out holds time series of the groundwater heads at each node and layer, and the file CVSubsidTecPlot.out holds time series of land-surface subsidence at each node and layer. These files can be used to produce 'movies' of groundwater heads and subsidence through time.

The IWFM Simulation program also prints out the Virtual Crop Characteristic File CVAvgET.out. This file contains a time series of the average root zone depth, minimum soil moisture requirement, crop evapotranspiration rate and irrigation efficiency for each model subregion.

Model Results – The IWFM Budget and Z-Budget Programs

The IWFM Budget program produces a number of detailed reports from binary output files generated by the IWFM Simulation program. The Budget program parameters are specified in the Budget Main Input File.

Budget Main Input File

The Budget Main Input File CVBudget.in specifies how the Budget program will process binary files for the C2VSim simulation for the time period from October 1, 1921 through September 30, 2009 with output for each month.

The File Description section of the Budget Main Input File lists the names of the binary files produced by the IWFM Simulation program. The Budget program reads each binary file and produces a text file with the same base name and the extension 'BUD'. For C2VSim, the Budget program produces the Land and Water Use Budget (CVlandwater.BUD from CVlandwater.bin), Stream Flow Budget (CVstream.BUD from CVstream.bin), Stream Reach Budget (CVstreamrch.BUD from CVstreamrch.bin), Root Zone Moisture Budget (CVrootzn.BUD from CVrootzn.bin), Groundwater Budget (CVground.bin from CVground.bin), Small Watershed Flow Components Budget (CVsmwshed.BUD from CVsmwshed.bin), Lake Budget (CVlake.bin from CVlake.bin), and Diversion Details Budget (CVdiverdtl.BUD from CVdiverdtl.bin). The Element Sub-group Details Budget is not produced for C2VSim.

The Output Unit Control section is next. C2VSim uses a length unit of feet and a time unit of one month, as entered in the Pre-processor input file, and thus internal calculations use an area unit of square feet, a volume unit of cubic feet and a volumetric flow rate of cubic feet per month. The factors in this section convert values from the internal units to the desired output units, and the accompanying labels for the desired output unit types are written directly to the budget output files. The desired output length unit is feet (FACTLTOU = 1 and UNITLTOU = 'FEET'), the desired output area is acres (FACTAROU = 0.000022957 to convert from square feet to acres and UNITAROU = 'AC'), and the output volume unit is acre-feet (FACTVLOU = 0.000022957 to convert from cubic feet to acre-feet and UNITVLOU = 'AC.FT.'). The next section has the Output Cache Size. The value of CACHE controls how often the Budget program writes results to output files; a larger value of CACHE generally corresponds to shorter run times, but if the value is too high it may cause a computer memory overflow error. CACHE is set to 5000000 for C2VSim.

The Budget Output Control Options section is next. The first part, with entries for models without time tracking, is commented out with asterisks. The second part lists the initial time 09/30/1921_24:00 (input item BDT), the same as the Simulation Main Input File, and ending time 09/30/2009_24:00 (EDT), any time after the initial time; if this time is after the ending time listed in the Simulation Main Input File, the Budget program only processes information up to the Simulation ending time.

The Budget program can aggregate results for multiple time steps. C2VSim uses a time step of one month, so the minimum time period for the Budget program is one month. The Budget Main Input File CVBudget.in has a value of 1 for MPRNT, specifying that the results are printed for each month. The value of MPRINT can be changed to report results for different time periods, for example to 12 to provide an annual report.

The last section of the Budget Main Input File contains the Subregion Names and Print Options. The first item is the number of subregions modeled (NREGN = 21 for C2VSim). This is followed by one line for each model subregion, containing the subregion number (IR), in ascending order; a flag IPRINT indicating whether to process this subregion (1) or not (0); and the subregion name, a text field that is copied directly to the output files, which for C2VSim is the Depletion Study Area (DSA) number.

Z-Budget Input Files

The IWFM Z-Budget program reads the CVZB.bin binary file produced by the Simulation program, computes inflows and outflows for user-specified aquifer zones made up of groups of model elements, and produces detailed flow budgets for each zone. The Z-Budget output file has the same base name as the binary file, with the extension 'BUD,' and is generally re-named by the user with the base name of the Z-Budget input file. The binary CVZB.bin file contains detailed aquifer flow components for each model element face. The Z-Budget program can be run multiple times on a single CVZB.bin file, with each successive run using a different input file delineating a different configuration of zones and layers. Seven Z-Budget input files have been developed for C2VSim to produce budgets for the entire model area (zbudget_all.in), for each hydrologic region (zbudget_HRs.in), for each subregion (zbudget_SRs.in), for each element for all model layers (zbudget_elem.in), and for each element for each model layer (zbudget_elem_L1.in, zbudget_elem_L2.in, zbudget_elem_L3.in). The general structure of the Z-Budget input file is described here, followed by a section describing each of the Z-Budget input files included with C2VSim.

The Input and Output Control Data section of the Z-Budget input file begins with the name of the binary file produced by the Simulation program. The second line holds the name of the DSS file in which to store Z-Budget output; this is left blank to print the output to a text file. The ZEXTENT flag can be set to 1 to specify horizontal zones with all layers aggregated into each zone, or to 0 to specify three-dimensional zones with layers. The output volume unit is acre-feet, so FACTVLOU = 0.000022957 to convert from cubic feet to acre-feet, and UNITVLOU = 'AC.FT.'. The Output Cache Size section contains the value of CACHE, which controls how often the Z-Budget program writes results to output files; a larger value of CACHE generally corresponds to shorter run times. CACHE is set to 50000 for the basic C2VSim model.

The Z-Budget Output Control Options section is next. The first part, with entries for models without time tracking, is commented out with asterisks. The second part lists the initial time 09/30/1921_24:00 (input item BDT), the same as the Simulation Main Input File, and ending time 09/30/2009_24:00 (EDT), any time after the initial time; if this time is after the ending time listed in the Simulation Main Input File, the Z-Budget program only processes information up to the Simulation ending time.

The final two sections describe the zones to be used to aggregate Simulation results, and a budget table is printed to the output file for each zone. The lines in the Zone Information section contain two items if all layers are aggregated in each zone (ZEXTENT = 1) or three items if the layer is to be specified (ZEXTENT = 0). The Zone Print Options section indicates which of the specified zones are to be printed to the output file. The seven Z-Budget Main Input Files zbudget_all.in, zbudget_HRs.in, zbudget_SRs.in, zbudget_elem.in, zbudget_elem_L1.in, zbudget_elem_L2.in, and zbudget_elem_L3.in contain different information for these two sections, and are described separately below.

Entire Model Area

The Z-Budget Main Input File zbudget_all.in specifies one zone for the entire model area. All layers are aggregated to this single zone (ZEXTENT = 1). The Zone Information section has one line for each model element, listing the element number in ascending order, followed by the zone number '1'. The Zone Print Options section contains one line listing zone number '1'. For C2VSim, the output file is renamed zbudget_all.bud.

Hydrologic Regions

The Z-Budget Main Input File zbudget_HRs.in specifies five zones corresponding to the five hydrologic regions: (1) the Sacramento Basin (subregions 1-7), (2) Eastside Streams (subregion 8), (3) Sacramento-San Joaquin Delta (subregion 9), (4) San Joaquin Basin (subregions 10-13), and (5) Tulare Basin (subregions 14-21). All layers are aggregated to these zones (ZEXTENT = 1). The Zone Information section has one line for each model element, listing the element number in ascending order, followed by the zone number (the corresponding hydrologic region number). The Zone Print Options section contains five lines listing the zone numbers 1-5. For C2VSim, the output file is renamed zbudget_HRs.bud.

Subregions

The Z-Budget Main Input File zbudget_SRs.in specifies 21 zones, corresponding to the 21 model subregions. All layers are aggregated to these zones (ZEXTENT = 1). The Zone Information section has one line for each model element, listing the element number in ascending order, followed by the zone number (the subregion number). The Zone Print Options section contains 21 lines listing the zone numbers 1-21. For C2VSim, the output file is renamed zbudget_SRs.bud.

Elements

Four Z-Budget Main Input Files tabulate flows for each groundwater element. The Z-Budget input file zbudget_Elem.in specifies one zone for each model element, incorporating all model layers. The Z-Budget input files zbudget_Elem_L1.in, zbudget_Elem_L2.in, and zbudget_Elem_L3.in also specify one zone for each model element, for the top, middle and bottom model layers, respectively.

In the Z-Budget input file zbudget_Elem.in, all layers are aggregated in each zone (ZEXTENT = 1). The Zone Information section has one line for each model element, listing the element number in ascending order, followed by the zone number (the element number). The Zone Print Options section contains a list of the element numbers. For C2VSim, the output file is renamed zbudget_Elems.bud.

In the Z-Budget input files zbudget_Elem_L1.in, zbudget_Elem_L2.in, and zbudget_Elem_L3.in, all zones occupy a single model layer (ZEXTENT = 0). The Zone Information section has one line for each model element, listing the element number in ascending order, followed by the model layer number (1 in zbudget_Elem_L1.in, 2 in zbudget_Elem_L2.in, and 3 in zbudget_Elem_L3.in) and the zone number (the element number). The Zone Print Options section contains a list of the element numbers. For C2VSim, the output files are renamed zbudget_Elem_L1.bud, zbudget_Elem_L2.bud, and zbudget_Elem_L3.bud, respectively. A Z-Budget program input file could be created containing all three layers, but it is easier to work with a single output file for each model layer.

Land Surface Process Reports

The Land Surface Process calculates the water balance between inputs and outputs to the land surface, and estimates the amount of groundwater pumping required to meet agricultural and urban demands. The Root Zone Budget reports the root zone water balance for each land use type, including the partitioning of precipitation into infiltration and runoff, the amount and sources of applied water, return flows, deep percolation, and changes in root-zone water storage. The Land and Water Use Budget reports the supply requirement to meet calculated demands after using root-zone moisture, the amount of groundwater and surface water available to meet these demands (after subtracting delivery losses), and any surplus or shortage.

Root Zone Moisture Budget

The Root Zone Moisture Budget is produced from information stored in the Simulation program binary output file CVrootzon.bin and is written to the file CVrootzn.BUD. This file has 21 subregional tables followed by a table labeled 'subregion 22', which reports values for the entire model area. All budget columns are in volumetric units except those related to time and area. The Root Zone Moisture Budget has 36 columns in each subregional budget table. Column 1 contains the time step, columns 2-14 contain values for the area under agricultural cultivation, columns 15-27 contain values for the urban area, and columns 28-36 contain values for the areas of native and riparian vegetation.

Within the agricultural section, column 2 contains the agricultural acreage, columns 3-8 detail the inputs from precipitation and irrigation water, and columns 9-14 detail the root-zone soil moisture balance. Within the inputs section, columns contain the volume of precipitation, runoff, applied irrigation water from surface water diversions, groundwater pumping and re-use, and net return flow. Within the root-zone soil moisture balance section, columns contain the volume of initial root-zone soil moisture storage, net changes in the root-zone soil moisture storage due to changes in land-use allocation, infiltration, losses to evapotranspiration, losses to deep percolation, and final root-zone soil moisture storage.

Within the urban section, column 15 contains the urban acreage, columns 16-20 detail the inputs from precipitation and irrigation water, and columns 22-27 detail the root-zone soil moisture balance. Within the water inputs section, columns contain the volume of precipitation, runoff, applied irrigation water from surface water diversions, groundwater pumping and re-use, and net return flow. Within the root-zone soil moisture balance section, columns contain the volume of initial root-zone soil moisture storage, net changes in the root-zone soil moisture storage due to changes in land-use allocation, infiltration, losses to evapotranspiration, losses to deep percolation, and final root-zone soil moisture storage.

Native and riparian land uses are combined in a single section. Column 28 contains the acreage, columns 29-30 detail the inputs from precipitation, and columns 31-36 detail the root-zone soil moisture balance. There are only two columns in the water inputs section, detailing the volume of precipitation and runoff, as there is no irrigation for these two land use classes. Within the root-zone soil moisture balance section, columns contain the volume of initial root-zone soil moisture storage, net changes in the root-zone soil moisture storage due to changes in land-use allocation, infiltration, losses to evapotranspiration, losses to deep percolation, and final root-zone soil moisture storage.

Land and Water Use Budget

The Land and Water Use Budget file is produced from information stored in the Simulation program binary output file CVlandwater.bin, and is written to the file CVlandwater.BUD. This file contains 21 subregional tables, followed by a table labeled 'subregion 22' which reports values for the entire model area. All budget columns are in volumetric units except those related to time and area.

The Land and Water Use Budget file has 16 columns in each subregional budget table. Column 1 contains the time step, columns 2-8 contain values for the agricultural area, columns 9-14 contain values for the urban area, and columns 15-16 contain regional water imports and exports. Within the agricultural section, columns contain the agricultural acreage, amount of water required to meet crop evapotranspirative demands, agricultural water supply requirement, groundwater pumping volume used for agriculture, surface water diversion volume used for agriculture, agricultural water supply shortage or surplus, and the amount of surface-water return flow re-used within the agricultural area. Within the urban section, columns contain the urban acreage, the urban water supply requirement, groundwater pumping volume used to meet urban demand, surface water diversion volume used to meet urban demand, urban water supply shortage or surplus, and the amount of surface-water return flow re-used within the urban area. The regional imports are the sum of surface water diversions and groundwater pumping originating outside the subregion or outside the model boundary, and the regional exports are the sum of surface water diversions and groundwater pumping exported to other subregions or outside the model boundary.

Root Zone Budget Example Figures

The Root Zone Budget provides information on water flows through the land surface process, summarized for each model subregion. Several examples are provided here detailing how this information can be presented. The data in figures 14-22 was created by running the Budget program using an MPRINT value of 12 in the file CVBudget.in. Figure 14 shows the sum of the values in the precipitation columns for the three land use types from the 'subregion 22' table. Figure 15 was created by summing the precipitation for the three land use types for subregions 1-7 (HR 1), subregion 8 (HR 2), subregion 9 (HR 3), subregions 10-13 (HR 4), and subregions 14-21 (HR 5). Figures 16 and 17 were created in the same way using the Actual ET columns. Figures 18 and 19 were created using the Actual ET column for each land use type from the 'subregion 22' table, and figure 20 was created using the Prime Applied Water columns from the 'subregion 22' table. Figures 21 and 22 summarize the inflows and outflows from the 'subregion 22' table

Figure 14. Annual precipitation volumes for California's Central Valley.

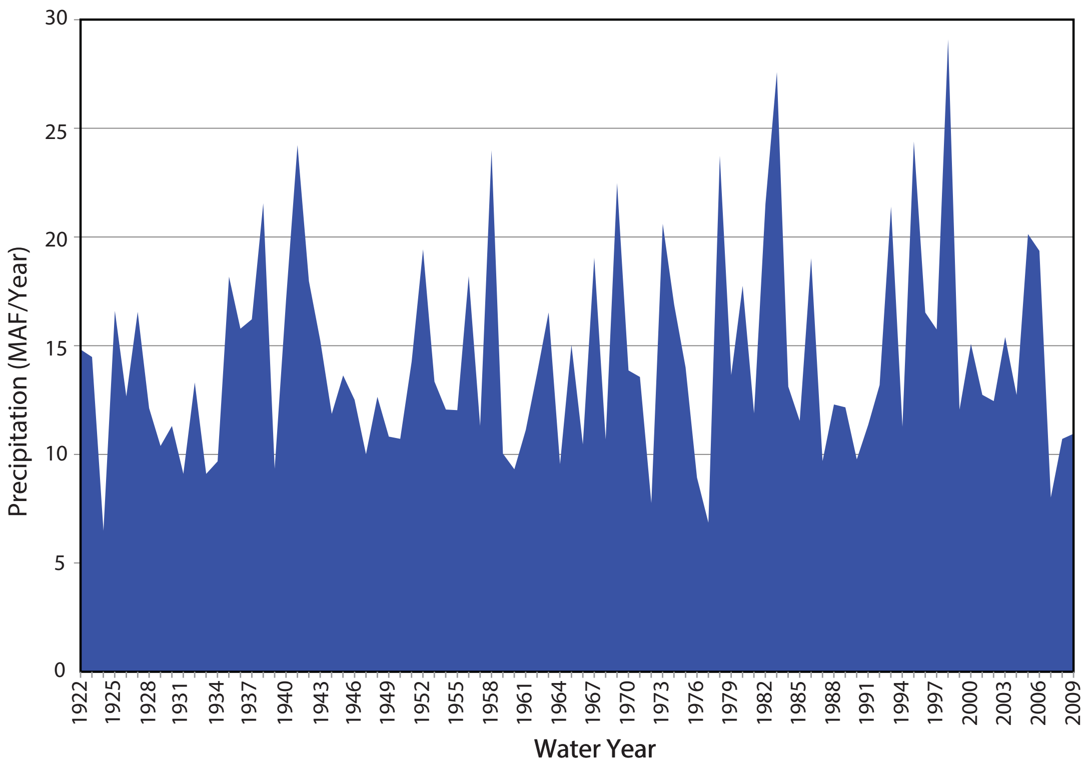


Figure 15. Regional precipitation distribution for water years 2000-2009.

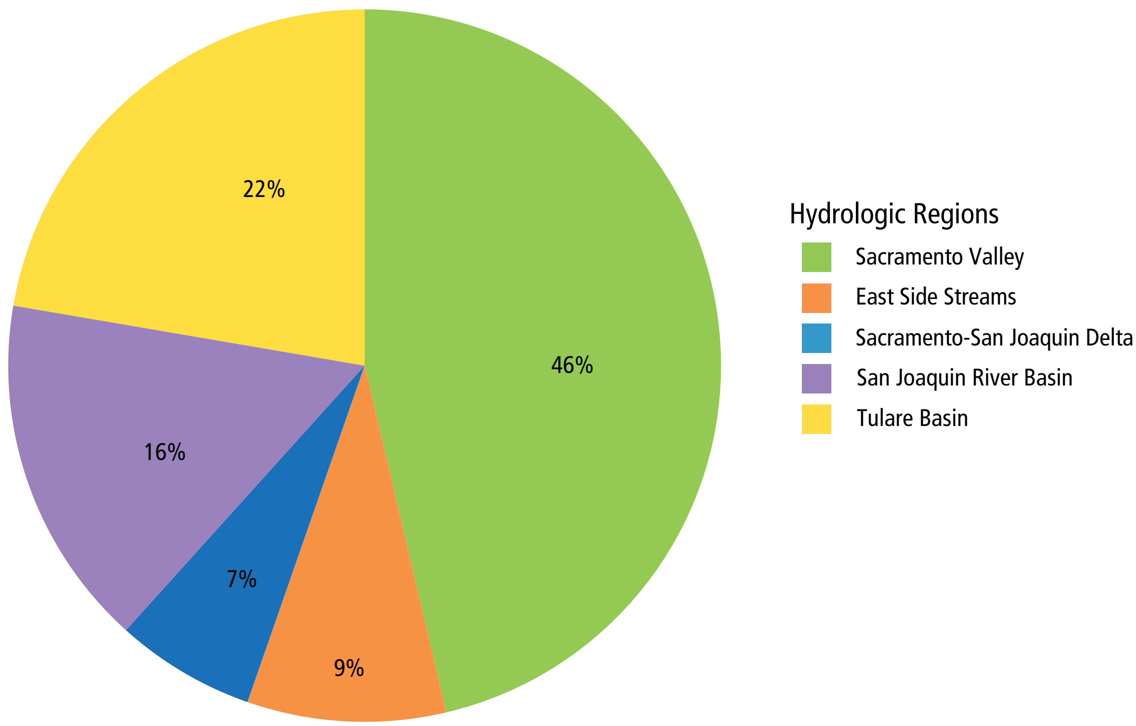


Figure 16. Simulated annual actual evapotranspiration for California's Central Valley for water years 1922-2009.

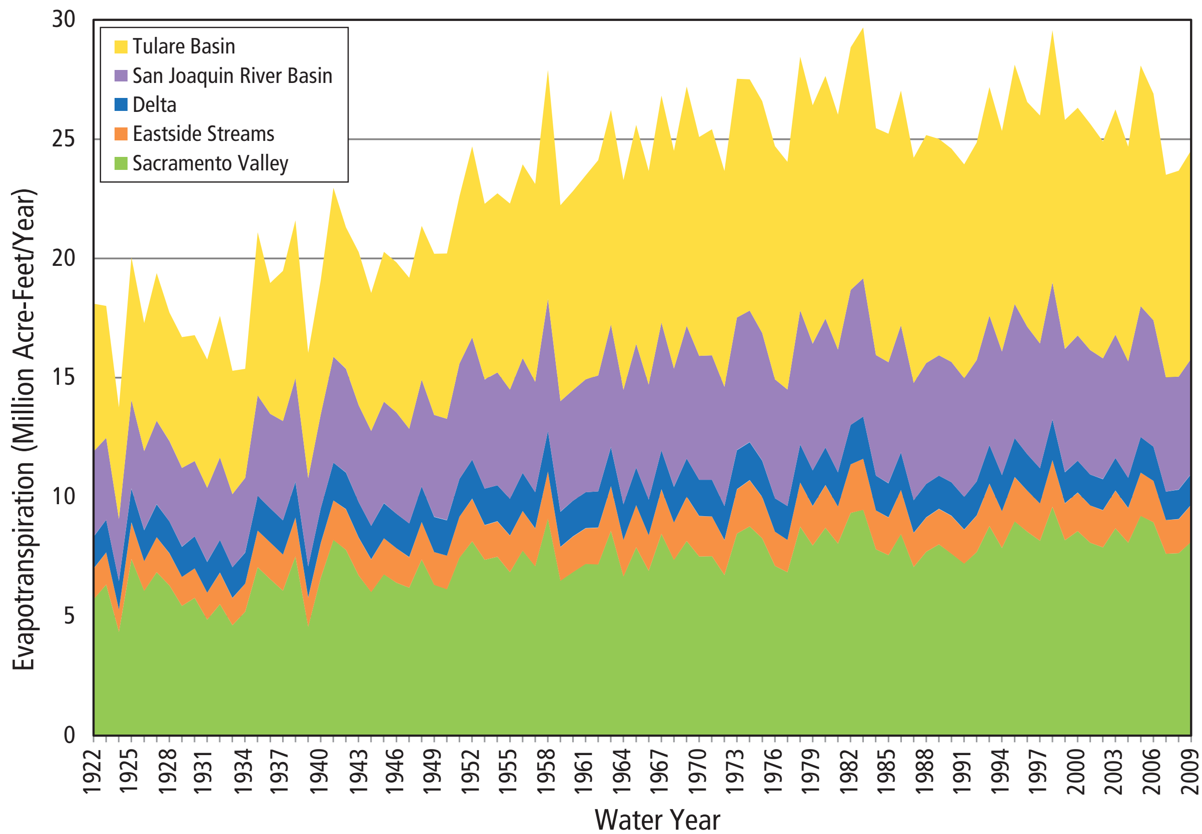


Figure 17. Regional distribution of simulated actual evapotranspiration for water years 2000-2009.

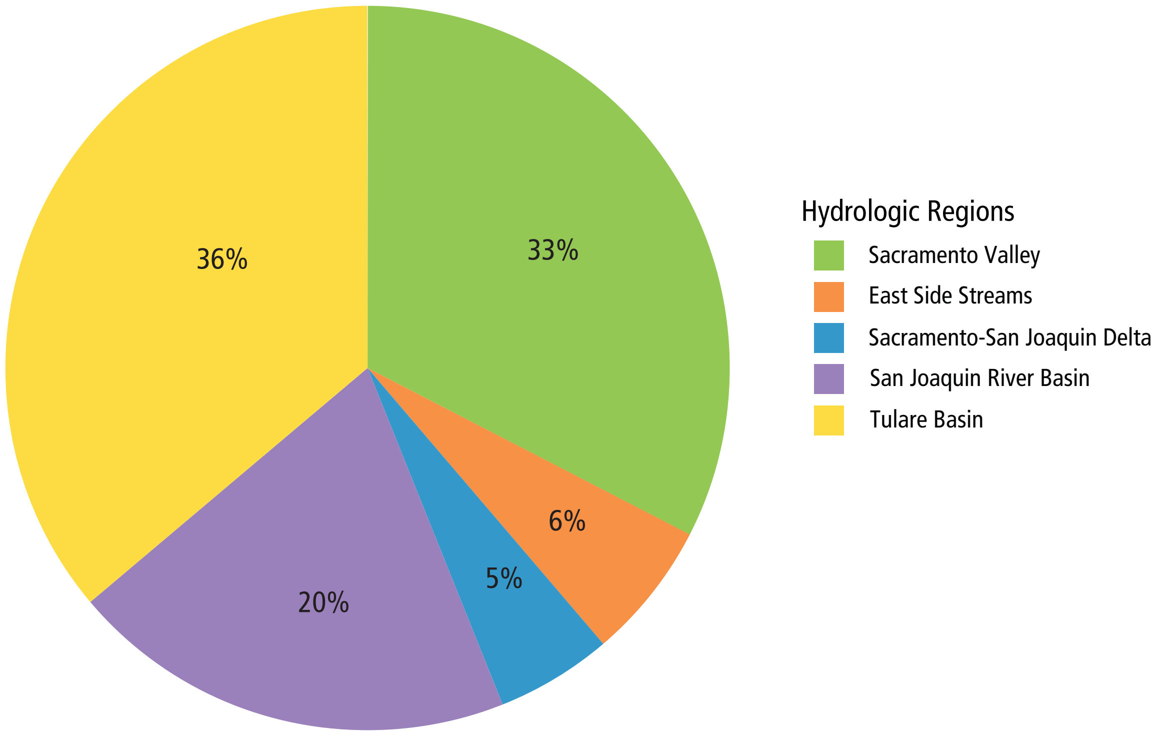


Figure 18. Simulated annual actual evapotranspiration by land use type for California's Central Valley for water years 1922-2009.

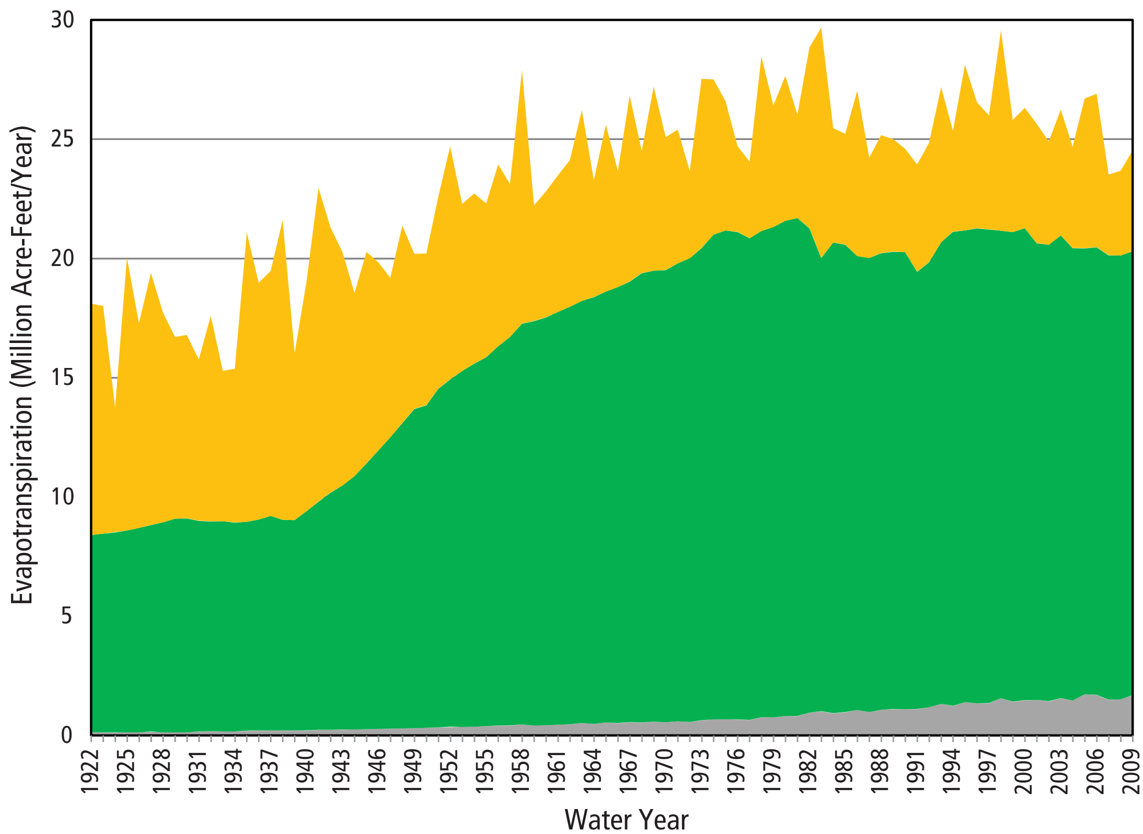


Figure 19. Distribution of simulated actual evapotranspiration by land use type for water years 2000-2009.

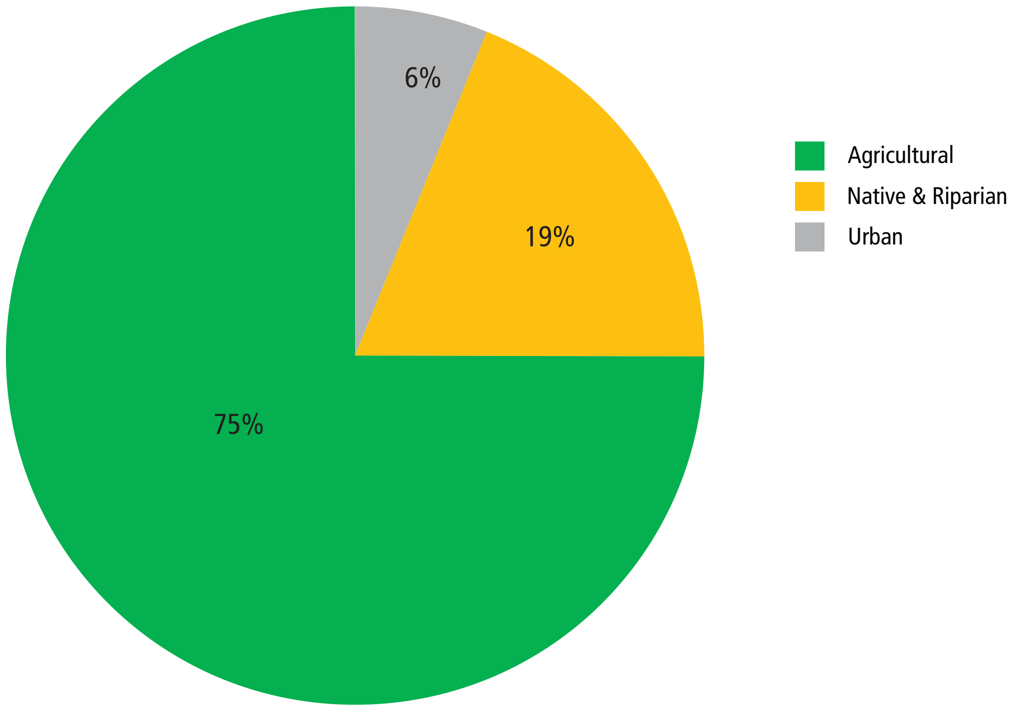


Figure 20. Simulated agricultural and urban water use in California's Central Valley for water years 1922-2009.

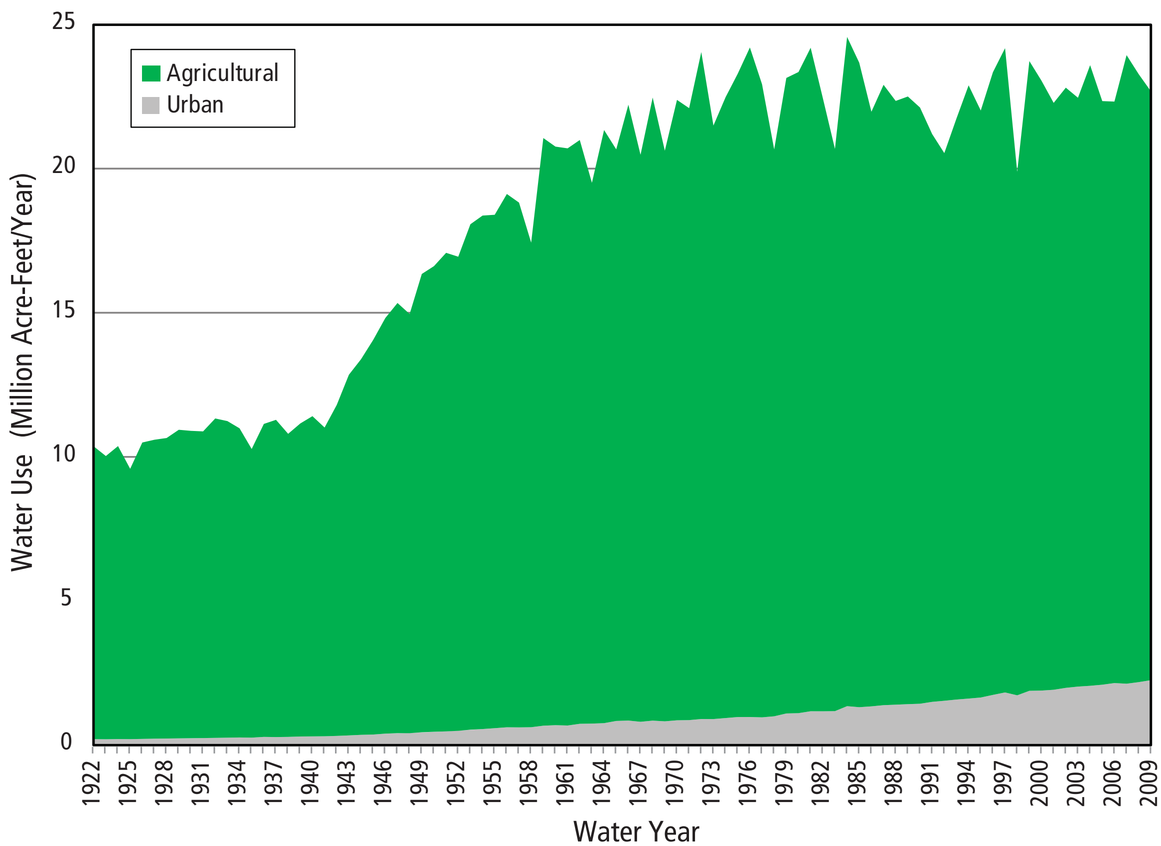


Figure 21. Simulated average water use and supply for California's Central Valley for each decade from the 1920's through the 2000's.

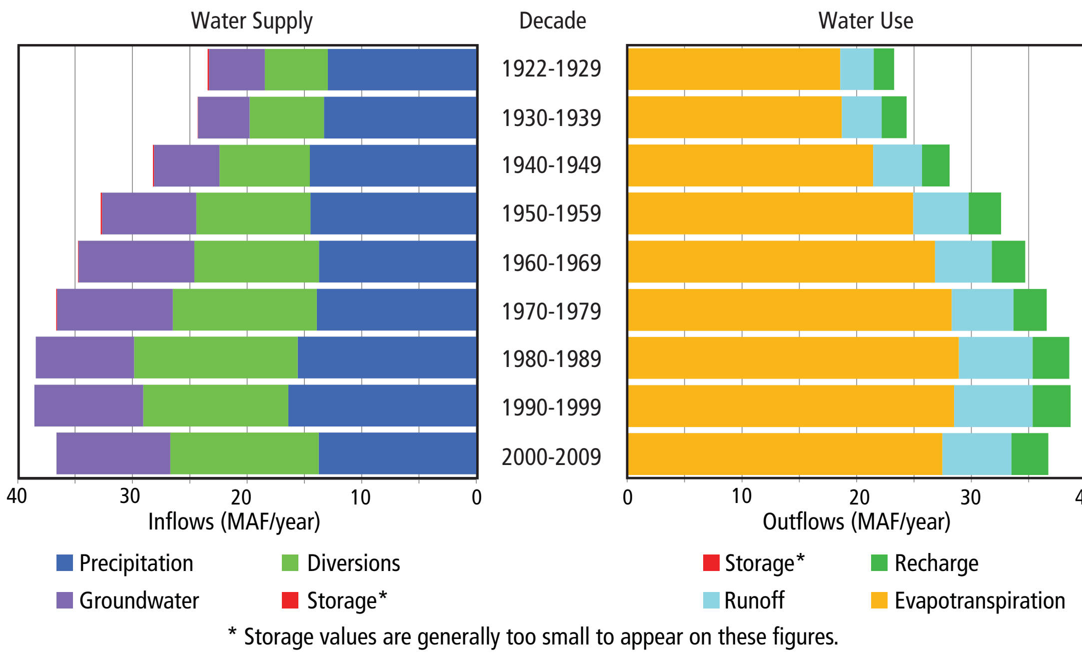
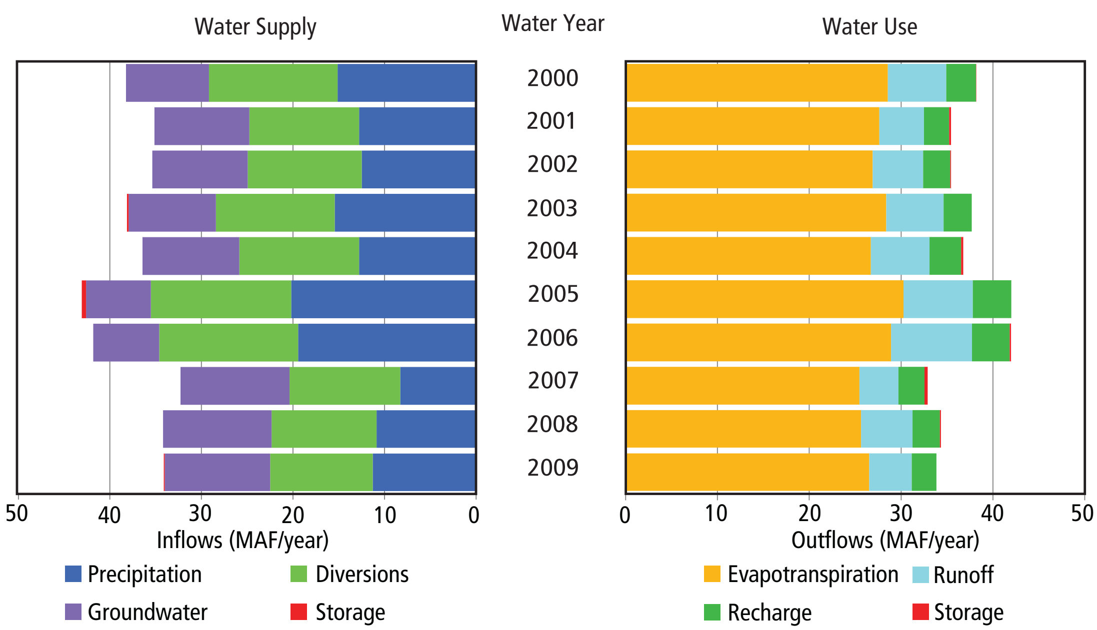


Figure 22. Simulated water use and supply for California's Central Valley for water years 2000-2009.



Land and Water Use Budget Examples

The Land and Water Use Budget provides information on water use by each land use type in the land surface process, summarized for each model subregion. Several examples are provided here detailing how this information can be presented. The data in figures 23-28 was created by running the Budget program using an MPRINT value of 12 in the file CVBudget.in. Figure 23 shows the values in the Pumping columns and figure 24 shows the values in the Diversion columns for the agricultural and urban land use types from the 'subregion 22' table. Figures 25 and 26 present the same data columns, grouping the agricultural land use in figure 25 and the urban land use in figure 26.

Figures 27 and 28 were created by summing the Pumping and Diversion columns for the agricultural and urban land use types for subregions 1-7 (HR 1), subregion 8 (HR 2), subregion 9 (HR 3), subregions 10-13 (HR 4), and subregions 14-21 (HR 5) for water years 2000-2009 and then taking their averages.

Figure 23. Simulated agricultural and urban groundwater use in California's Central Valley for water years 1922-2009.

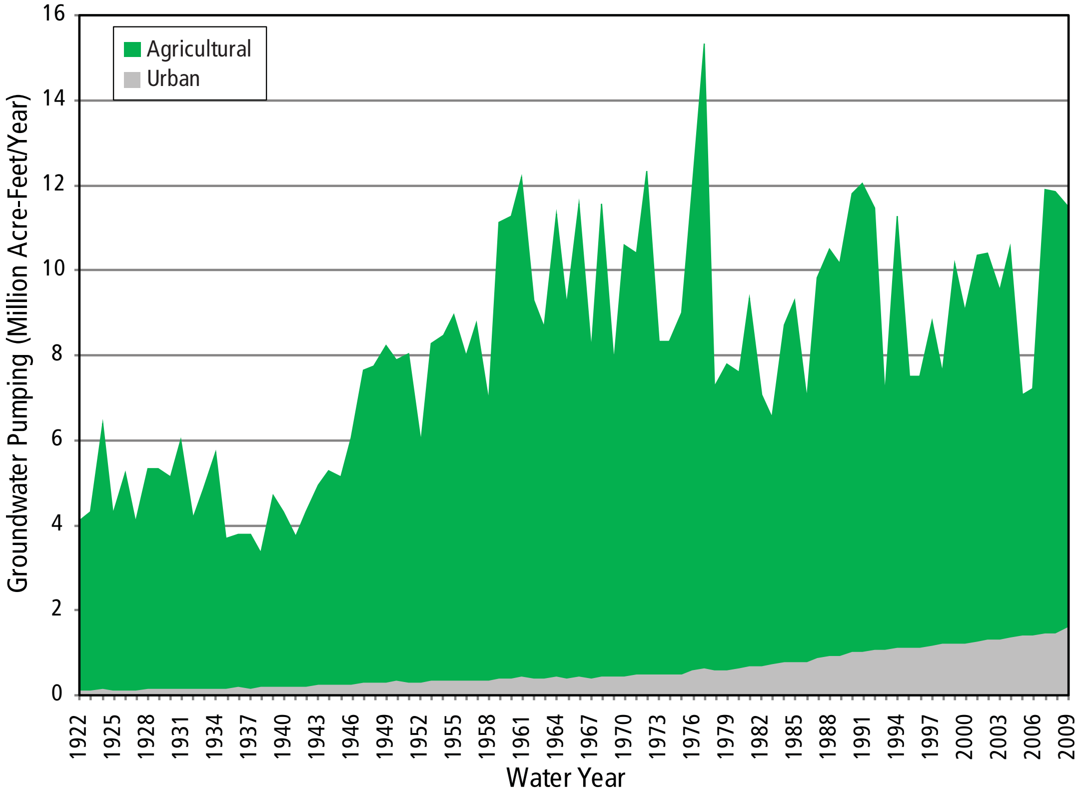


Figure 24. Simulated agricultural and urban surface water use in California's Central Valley for water years 1922-2009.

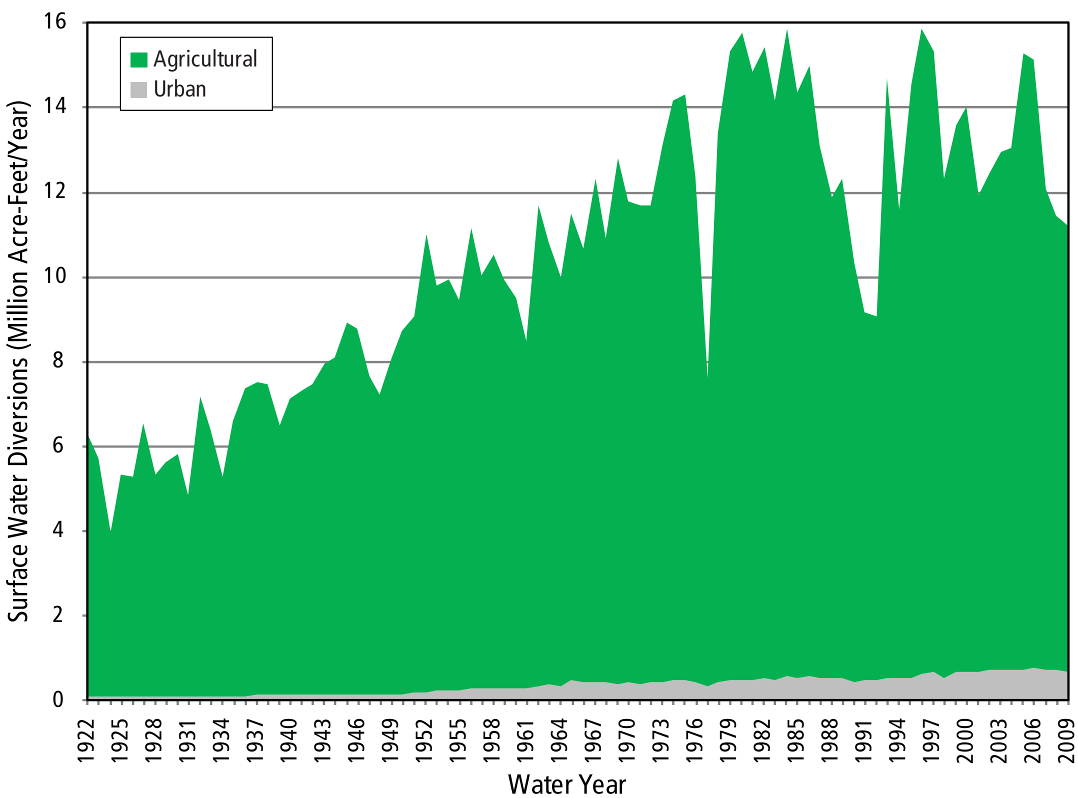


Figure 25. Simulated water supplies for agricultural use in California's Central Valley for water years 1922-2009.

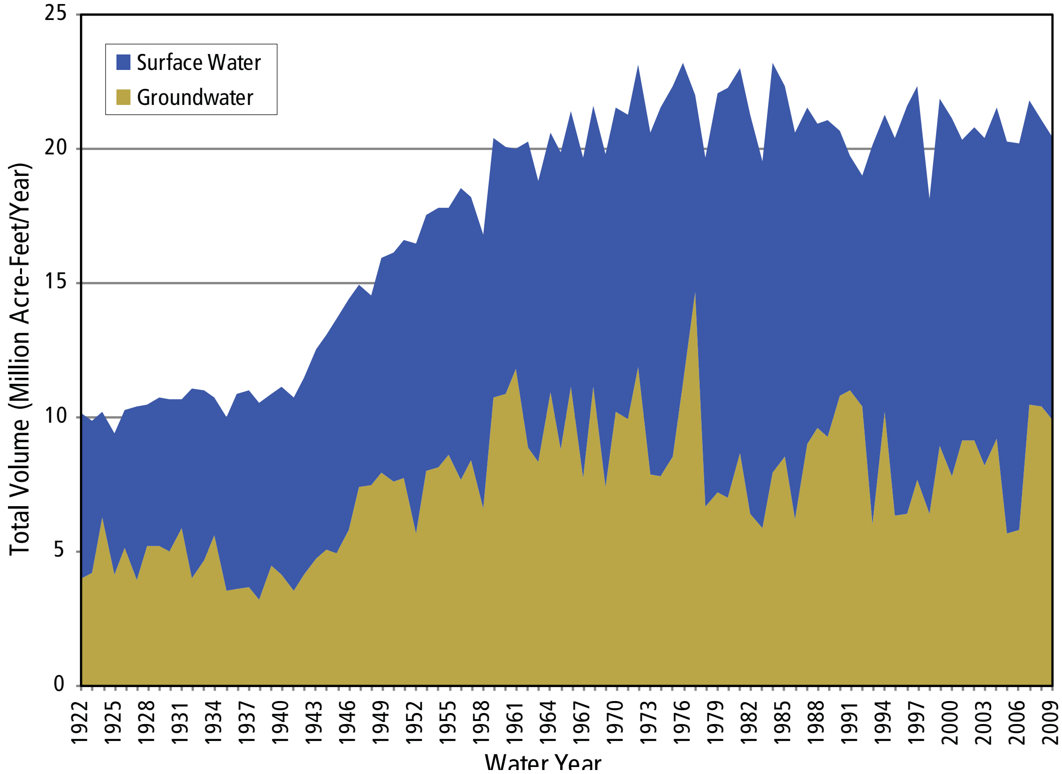


Figure 26. Simulated water supplies for agricultural use in California's Central Valley for water years 1922-2009.

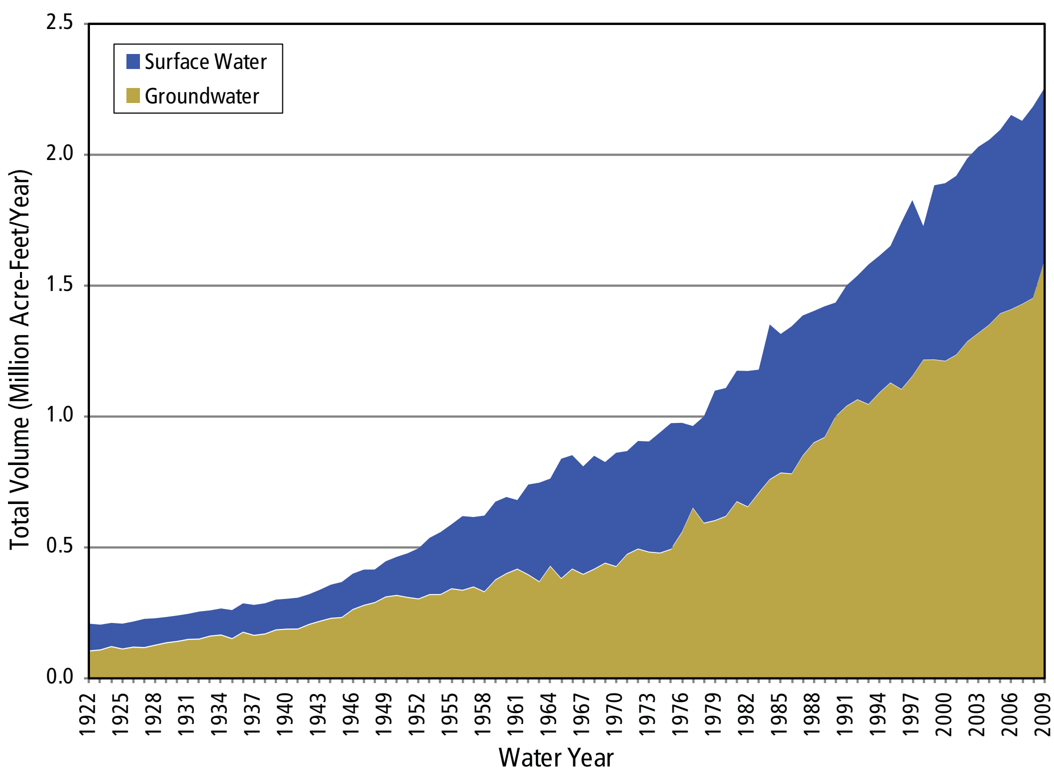


Figure 27. Regional distribution of simulated groundwater use for water years 2000-2009.

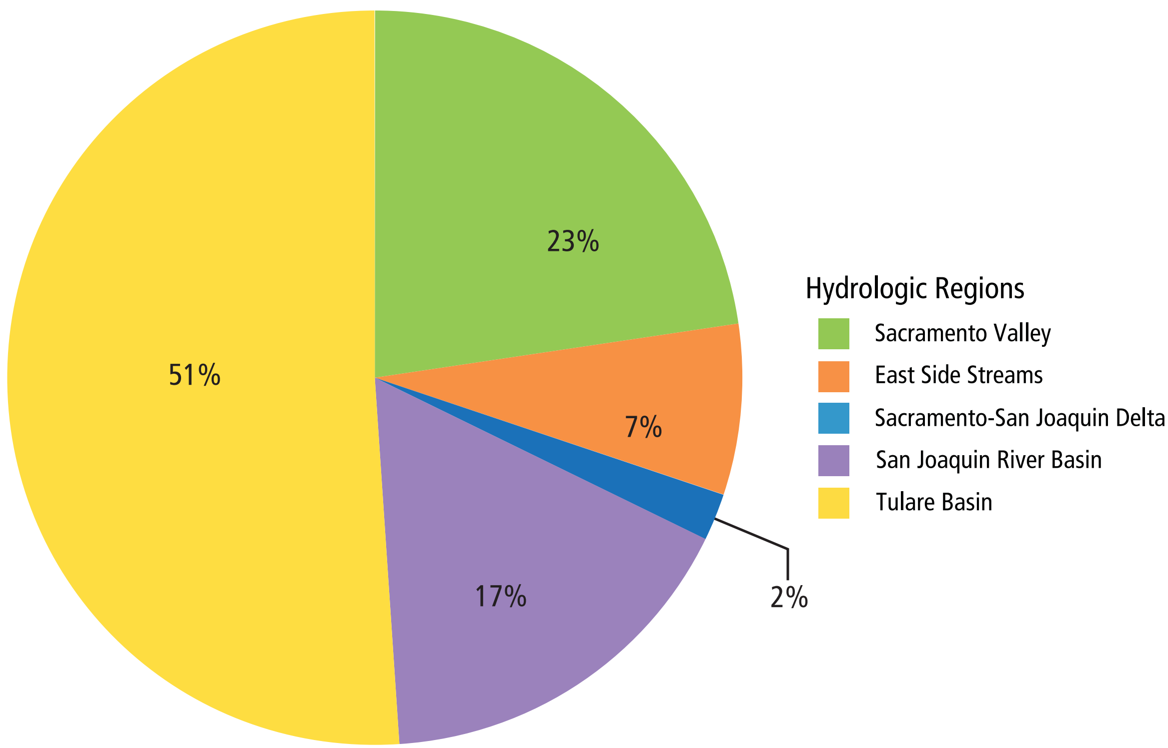
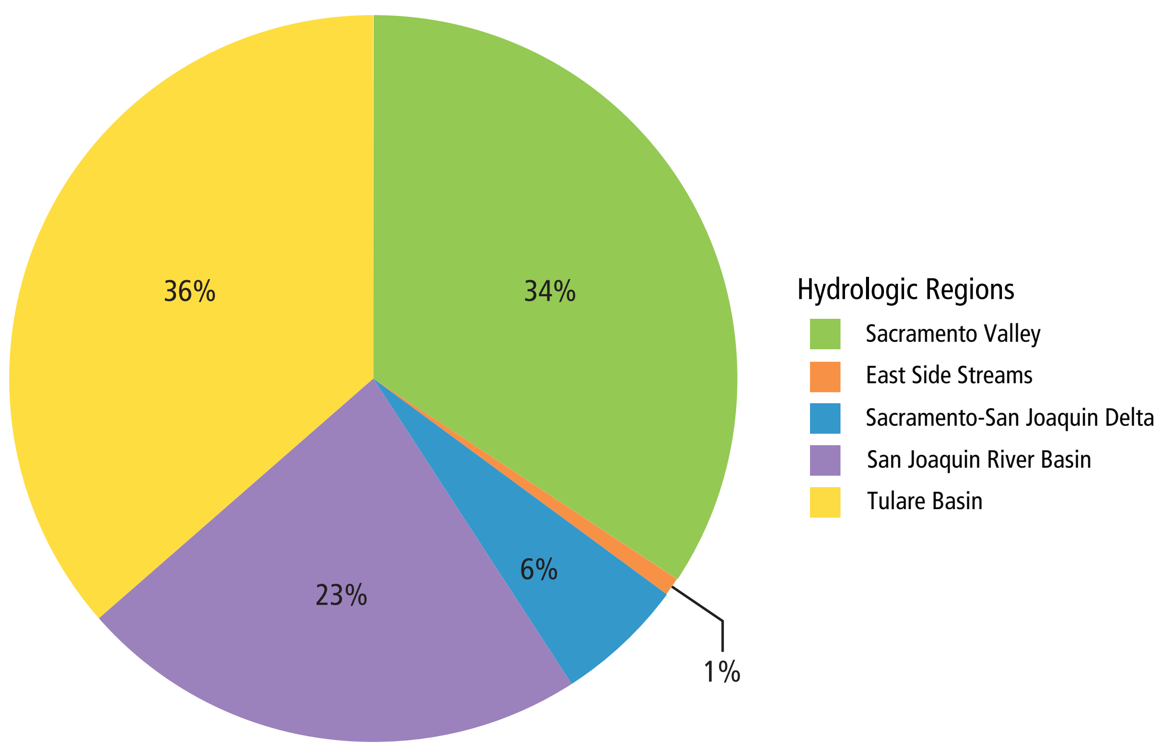


Figure 28. Regional distribution of simulated surface water use for water years 2000-2009.



Surface Water Flow Process Reports

The Surface Water Process calculates water movement through the rivers and lakes, with inflows from runoff and return flow, outflows to surface water diversions, exchanges between river reaches via bypasses, and exchanges with the groundwater aquifer. The Stream Budget, Stream Reach Budget and Lake Budget report water balances for each time step. The Diversion Details Budget lists the volume of water diverted and delivered for each surface water diversion.

Stream Flow Budget

The Stream Flow Budget is produced from information stored in the binary file CVstream.bin created by the Simulation program at run-time and is output to the file CVstream.BUD. Each river reach is assigned to a subregion in the Pre-processor input file CVstream.dat. Information is reported by subregion, with 21 subregional tables followed by a table labeled 'subregion 22', which reports values for the entire model area. The Stream Flow Budget reports information on flows into and out of the subregion and flows to and from other processes including surface runoff, return flows, tile drain discharges, surface water diversions and bypasses, flows to and from groundwater and flows from small stream watersheds, and any unmet surface water diversions. All budget columns are in volumetric units except those related to time.

The Stream Flow Budget tables contain 13 columns for each subregion. Column 1 contains the time step, columns 2-4 contain the surface water inflows and outflows, columns 5-9 contain flows to and from other processes, columns 10 and 11 contain diversions and bypasses, column 12 contains the mass balance error, and column 13 contains the diversion shortage. Within the surface water inflows and outflows, column 2 lists inflows on reaches assigned to the subregion, column 3 lists outflows on reaches assigned to the subregion, and column 4 lists all 'tributary flows', surface water inflows from small-stream watersheds to reaches assigned to the subregion. Column 5 lists inflows from tile drains, column 6 lists direct runoff from precipitation, column 7 lists return flow from irrigation, column 8 lists flows to and from groundwater (a positive value indicates a net gain and a negative value indicates a net loss), and column 9 indicates inflow from lakes. Column 10 contains surface water diversions, and column 11 contains net bypass flow (inflows minus outflows) for the subregion. Column 13 contains the diversion shortage, the difference between surface water diversion requirements and available surface water; a value of zero indicates that all surface water diversion requirements were met for the time period.

Stream Reach Budget

The Stream Reach Budget is produced from information stored in the binary file CVstreamrch.bin created by the Simulation program at run-time and is output to the file CVstreamrch.BUD. The Stream Reach Budget has one table for each of the 75 simulated river reaches (figure 4). The budget columns are in volumetric units (except those related to time) and are identical to those in the Stream Flow Budget.

The Stream Reach Budget has 13 columns in each river reach budget table. Column 1 contains the time step, columns 2-4 contain the surface water inflows and outflows, columns 5-9 contain flows to and from other processes, columns 10 and 11 contain diversions and bypasses, column 12 contains the mass balance error, and column 13 contains the diversion shortage. Within the surface water inflows and outflows, column 2 lists the inflow at the head of the reach, column 3 lists the outflow at the end of the reach, and column 4 lists all 'tributary flows', surface water inflows from small-stream watersheds to the reach. Column 5 lists inflows from tile drains, column 6 lists direct runoff from precipitation, column 7 lists return flow from irrigation, column 8 lists flows to and from groundwater (a positive value indicates a net gain and a negative value indicates a net loss), and column 9 indicates inflow from lakes. Column 10 contains surface water diversions, and column 11 contains net bypass flow (inflows minus outflows) for the reach. Column 13 contains the diversion shortage, the difference between surface water diversion requirements and available surface water; a value of zero indicates that all surface water diversion requirements were met for the time period.

Lake Budget

The Lake Budget is produced from information stored in the binary file CVlake.bin created by the Simulation program at run-time and is output to the file CVlake.BUD. The Lake Budget contains one table for each simulated lake, which provides the water balance, including total storage and surface altitude, inflows from precipitation and outflows to evapotranspiration, and flows to and from other processes. The Lake Budget gives details for the two simulated lakes, (1) Buena Vista Lake and (2) Tulare Lake. All budget columns are in volumetric units except those related to time and lake surface altitude.

The Lake Budget has 11 columns. Column 1 contains the time step, columns 2 and 3 contain the beginning and ending storage volume, column 6 contains precipitation intercepted, column 8 contains evaporative losses, column 10 contains the mass balance error, and column 11 contains the lake surface altitude. Columns 4, 5, 7 and 9 detail flows to and from other processes. Column 4 contains inflows from upstream lakes, column 5 contains inflows from bypasses, column 7 lists flows to and from groundwater (a positive value indicates a net gain and a negative value indicates a net loss), and column 9 contains outflows from the lake.

Diversion Detail Budget

The Diversion Detail Budget is produced from information stored in the binary file CVdiverdtl.bin created by the Simulation program at run-time and is output to the file CVdiverdtl.BUD. The Diversion Detail Budget information is reported by subregion, with 21 subregional tables; no report is produced for the entire model area. All budget columns are in volumetric units except those related to time. Each item is listed in two paired columns, the first containing the volume diverted from a river node, and the second, in parentheses, containing any reduction below the specified amount. For each subregion, deliveries to the subregion are listed by diversion number in increasing order, followed by the diversions within the subregion listed by diversion number in increasing order. Thus a diversion from subregion A that supplies deliveries to subregion B would be listed as a diversion in the table for subregion A and as a delivery in the table for subregion B. Recoverable and nonrecoverable losses can be calculated as the difference between the diversion and delivery amounts.

Each subregional table contains three header lines. The first line contains the diversion number, the second line contains the river node the diversion is taken from, and the third header line contains (+) for deliveries and (-) for diversions. A river node value of zero for a delivery indicates the water was imported from outside the model boundary, and a river node value of zero for a diversion indicates the water was exported to an area outside the model boundary.

Stream Budget Example

The Stream Budget aggregates information to the subregion level, and is best used when information is aggregated by hydrologic region or for the entire model area. The data used to create figure 29 was created by running the Budget program using an MPRINT value of 12 in the file CVBudget.in, using the Gain from Groundwater column of the 'subregion 22' table.

Stream Reach Budget Examples

The Stream Reach Budget provides interesting information on the flows to and from each river reach. Perhaps the most interesting information is the groundwater-surface water flows, including how they differ locally and how they have changed through time. The data used to create part A of figure 30 was created by running the Budget program using an MPRINT value of 1 in the file CVBudget.in, and the data used to create part B of figure 30 was created by running the Budget program using an MPRINT value of 12 in the file CVBudget.in. Each figure was created using the data in the Gain from Groundwater column of the appropriate river reach table.

Figure 29A. Simulated net groundwater discharges to rivers in California's Central Valley for each decade from the 1920's through the 2000's.

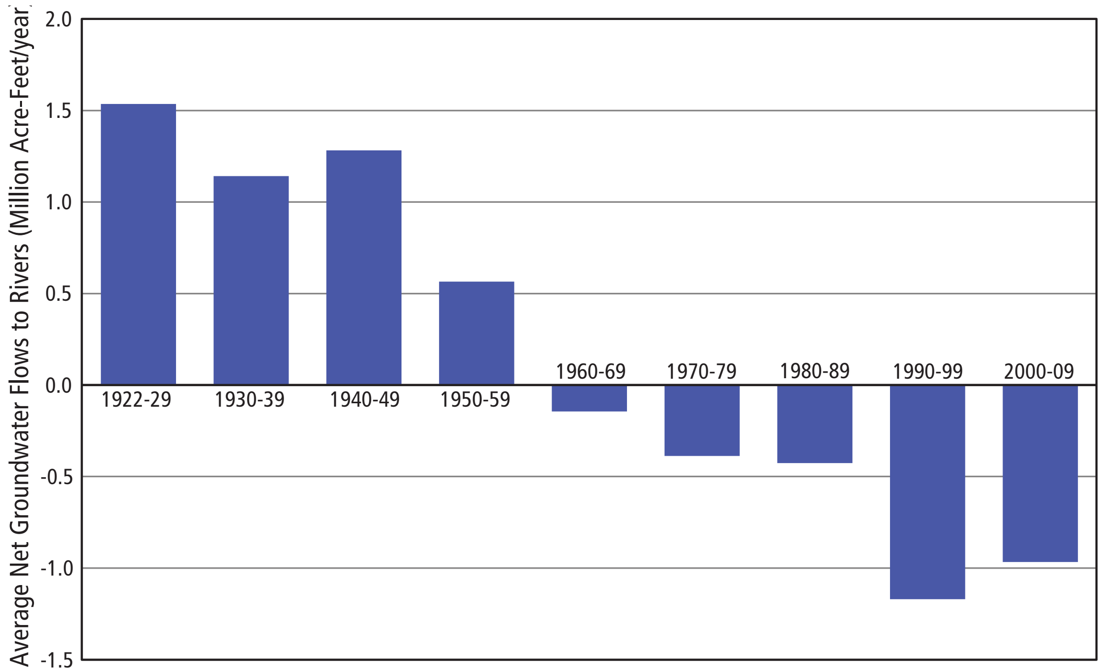


Figure 29B. Simulated net groundwater discharges to rivers in the Sacramento Valley for each decade from the 1920's through the 2000's.

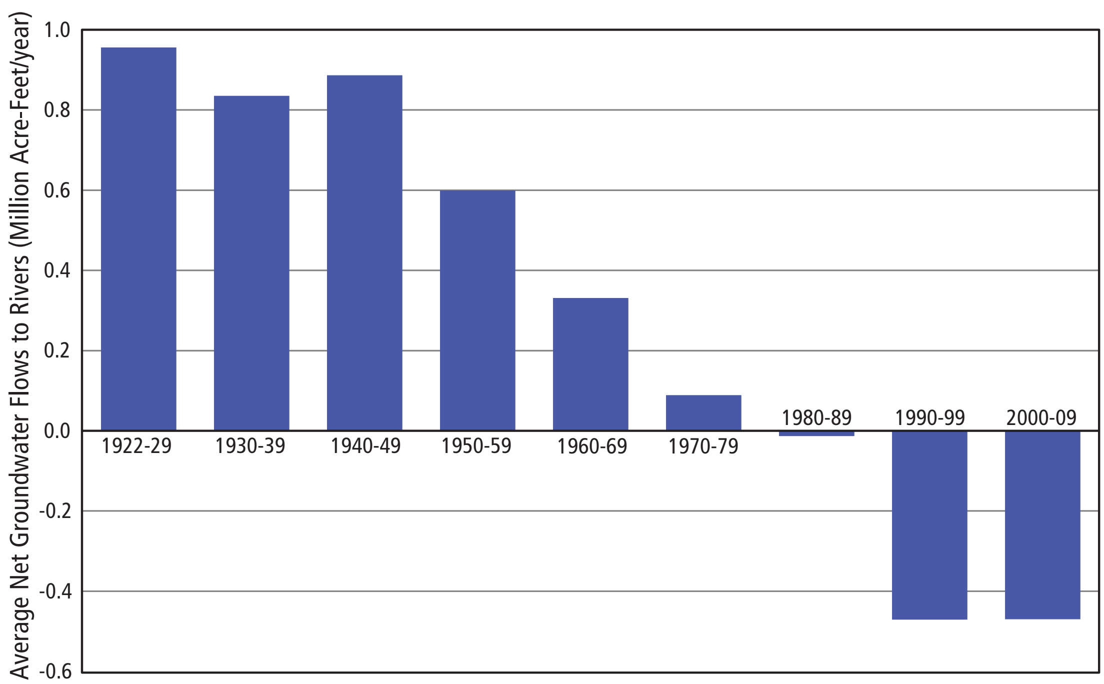


Figure 29C. Simulated net groundwater discharges to rivers in the San Joaquin Basin for each decade from the 1920's through the 2000's.

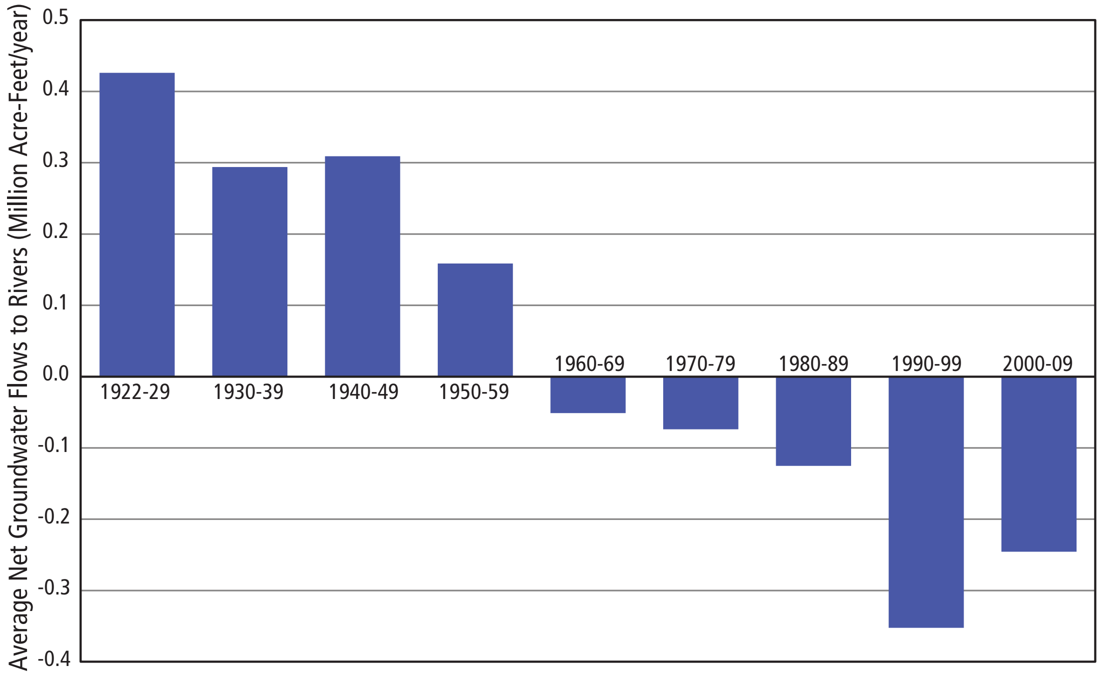


Figure 29D. Simulated net groundwater discharges to rivers in the Tulare Basin for each decade from the 1920's through the 2000's.

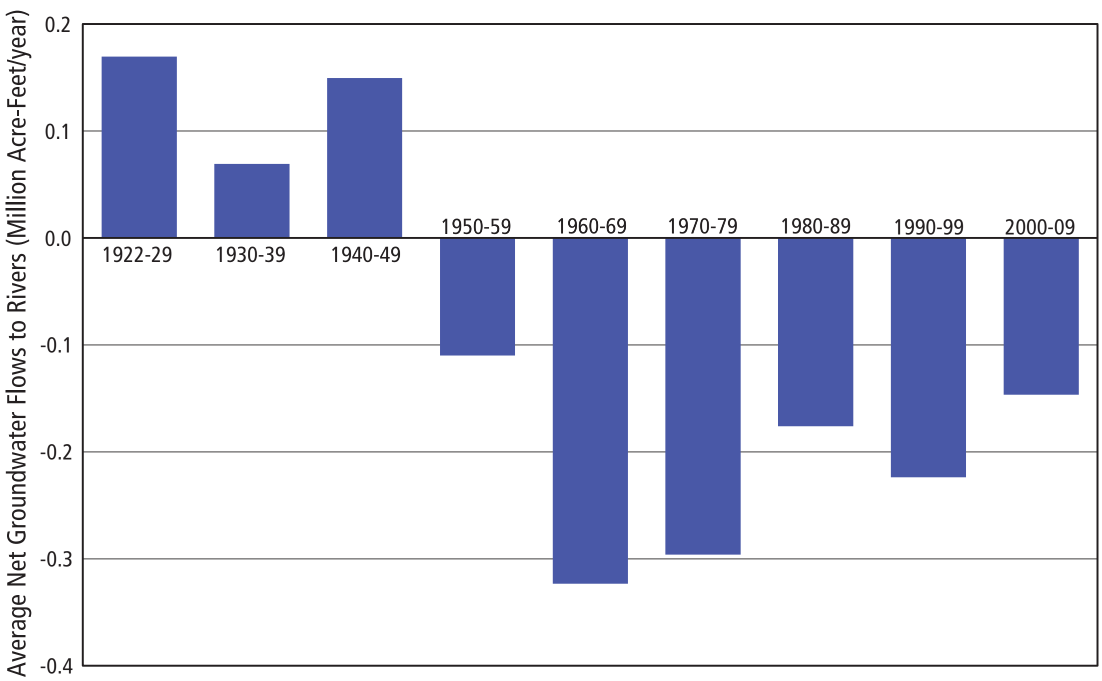
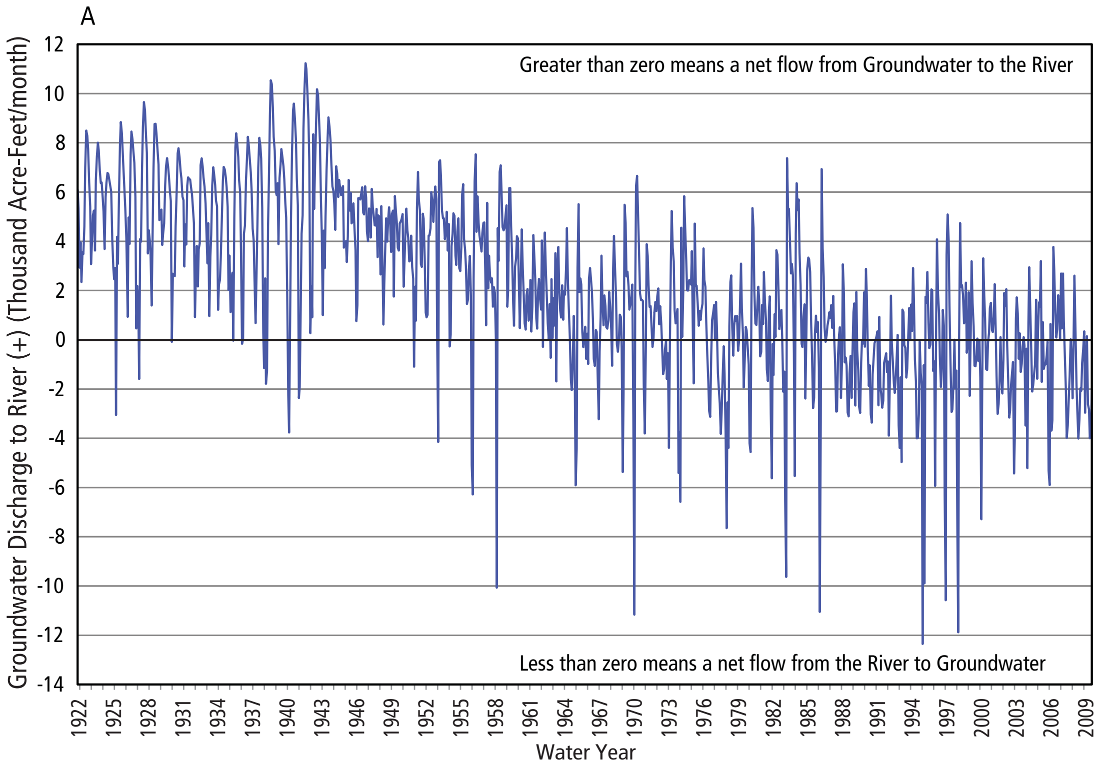
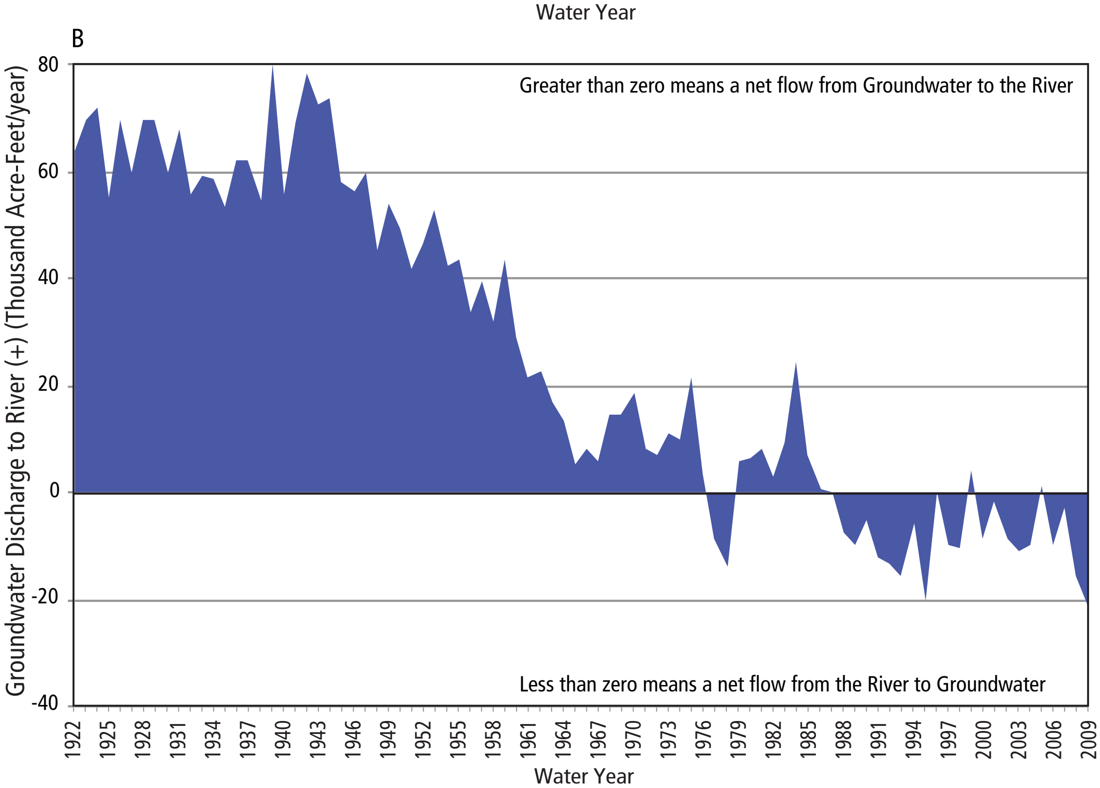


Figure 30. Simulated net groundwater discharges to the Sacramento River between Deer Creek and Stony Creek for water years 1922-2009. (A) Monthly and (B) Annually.





Diversion Detail Budget Examples

The process used to create figure 31 was complex, and used the Diversion Details Budget created by running the Budget program using an MPRINT value of 12 in the file CVBudget.in.

1) The diversion details budget was copied into an excel workbook, with one worksheet for each subregion. The worksheets were named 'SR01' through 'SR21'.

2) Two new worksheets were added, and formulas were used to aggregate the diversion amounts to one worksheet named 'DIVERSIONS' and the delivery amounts to the other worksheet, which was named 'DELIVERIES'.

3) A worksheet was added named 'LOSSES' and formulas were used to calculate the total losses for each time step, the difference between the diverted and delivered amounts.

4) A worksheet named 'DIVSPEC' was added and populated with the diversion details section of the diversion specification file CVdivspec.dat. The FRACRL and FRACNL values can be used to allocate the total losses to recoverable and non-recoverable losses. The number in the ICFSIRIG column indicates whether the diversion is for urban (22) or agricultural (23) use.

5) Two worksheets named 'AG' and 'URBAN' were added, and the ICFSIRIG values from the DIVSPEC worksheet were used to allocate individual deliveries to the two worksheets.

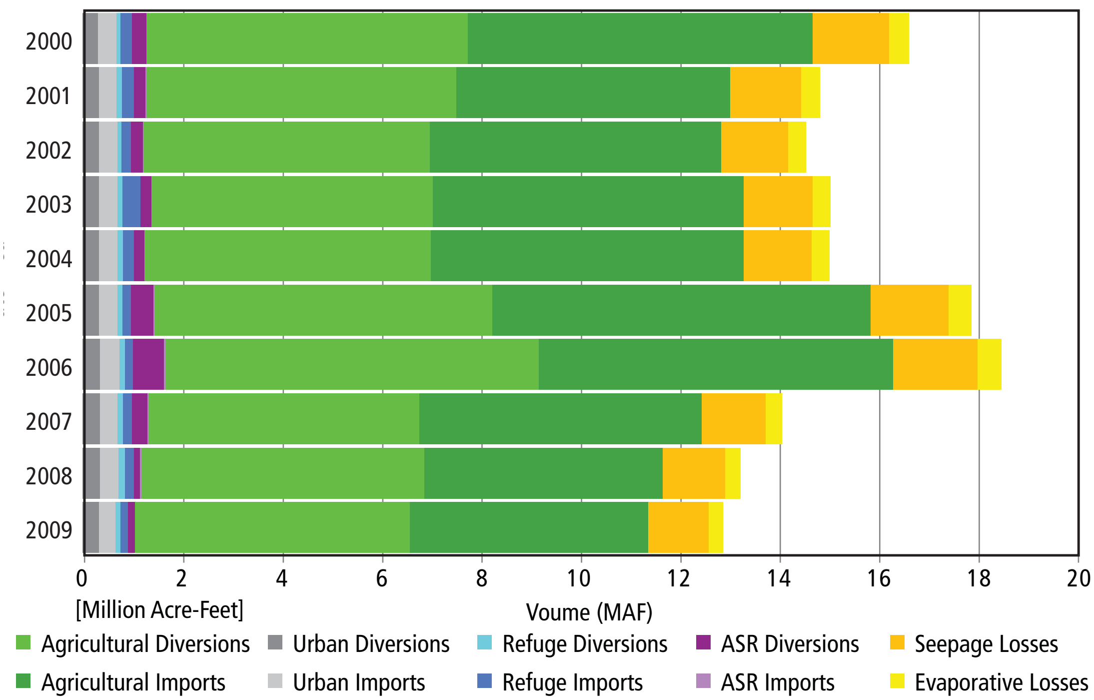
6) Four more worksheets named 'AG-DIV', 'AG-IMPORT', 'URBAN-DIV' and 'URBAN-IMPORT' were added to se the agricultural diversion deliveries, agricultural import deliveries, urban diversion deliveries and urban import deliveries. The origination river node was used to allocate values from worksheet AG to worksheets AG-DIV and AG-IMPORT and from worksheet URBAN to URBAN-DIV and URBAN-IMPORT.

7) Two more worksheets named 'RECOV-LOSSES' and 'NONREC-LOSSES' were added, and the values of FRACRL and FRACNL were used to allocate values from worksheet LOSSES to worksheets RECOV-LOSSES and NONREC-LOSSES.

8) A worksheet named 'SUMMARY' was added with the water year in the first column, and the sums of the rows in worksheets AG-DIV, AG-IMPORT, URBAN-DIV, URBAN-IMPORT, RECOV-LOSSES and NONREC-LOSSES in the next six columns.

The column chart in figure 31 was created using the table in the SUMMARY worksheet. Similar figures could be created for each subregion and each hydrologic region.

Figure 31. Simulated surface water destinations for California's Central Valley for water years 2000-2009.



Small-Stream Watersheds Process Report

The Small-Stream Watershed Process partitions precipitation into surface outflow and infiltration, then calculates evapotranspiration and recharge from the root-zone soil moisture, and then calculates groundwater outflows to surface discharge and base flow for each Small-Stream Watershed. Groundwater base flow enters the top aquifer layer at the specified groundwater node. Surface outflow and surface discharge are routed through a stream arc, with some water flowing to the groundwater system at each node.

Small-Stream Watershed Flow Components Budget

The Small-Stream Watershed Flow Components Budget Report is produced from information stored in the binary file CVsmwshed.bin created by the Simulation program at run-time and is output to the file CVsmwshed.BUD. The Small Watershed Flow Components Budget has one table for each small-stream watershed. The table columns list the time, total surface water outflow from runoff and groundwater outflow, groundwater base outflow, the sum of base flow and surface percolation, and the net outflow to surface streams. Surface water outflow from overland flow and from groundwater discharges to surface water in the small-stream watersheds cannot be determined from this budget.

Small-Stream Watersheds Example

The Small-Stream Watersheds Budget details the surface water and groundwater inputs from the 210 intermittent ungaged watersheds along the rim of the Central Valley. Subregional totals of groundwater base flow, surface percolation and net surface outflow to streams are also available from the Groundwater Budget, Stream Budget and Stream Reach Budget. The data for figures 32 and 33 was created by running the Budget program using an MPRINT value of 12 in the file CVBudget.in, and summing the values for small-stream watersheds 76-140 and 204-210 for HR1, 141-151 for HR2, 66-75 for HR3, 47-65 and 152-165 for HR4, and 1-47 and 166-203 for HR5. Figure 32 shows the total small-stream watershed surface water outflow for each hydrologic region and figure 33 shows the regional distribution of surface water inflow for water years 2000-2009.

Figure 32. Surface-water inows from small-stream watersheds, water years 1922-2009.

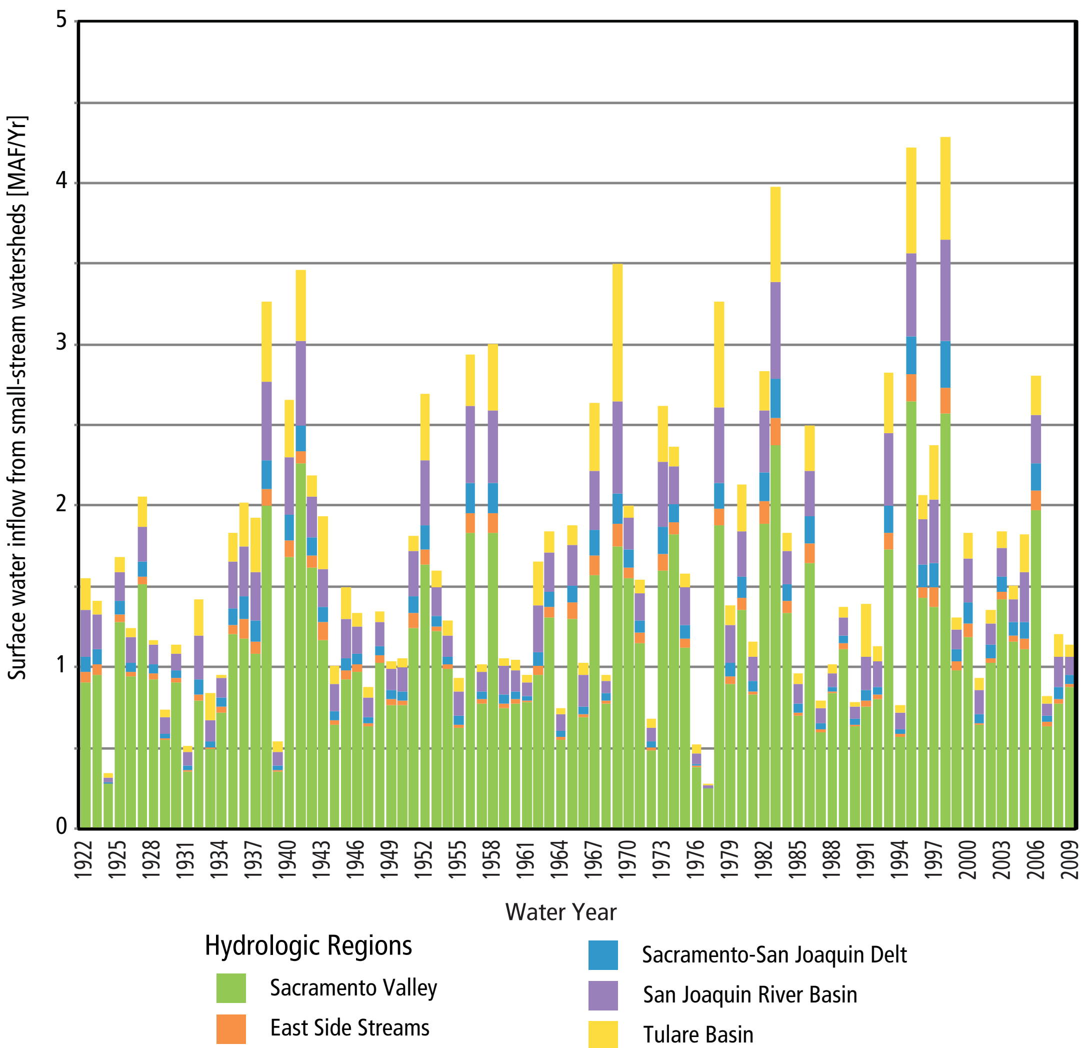
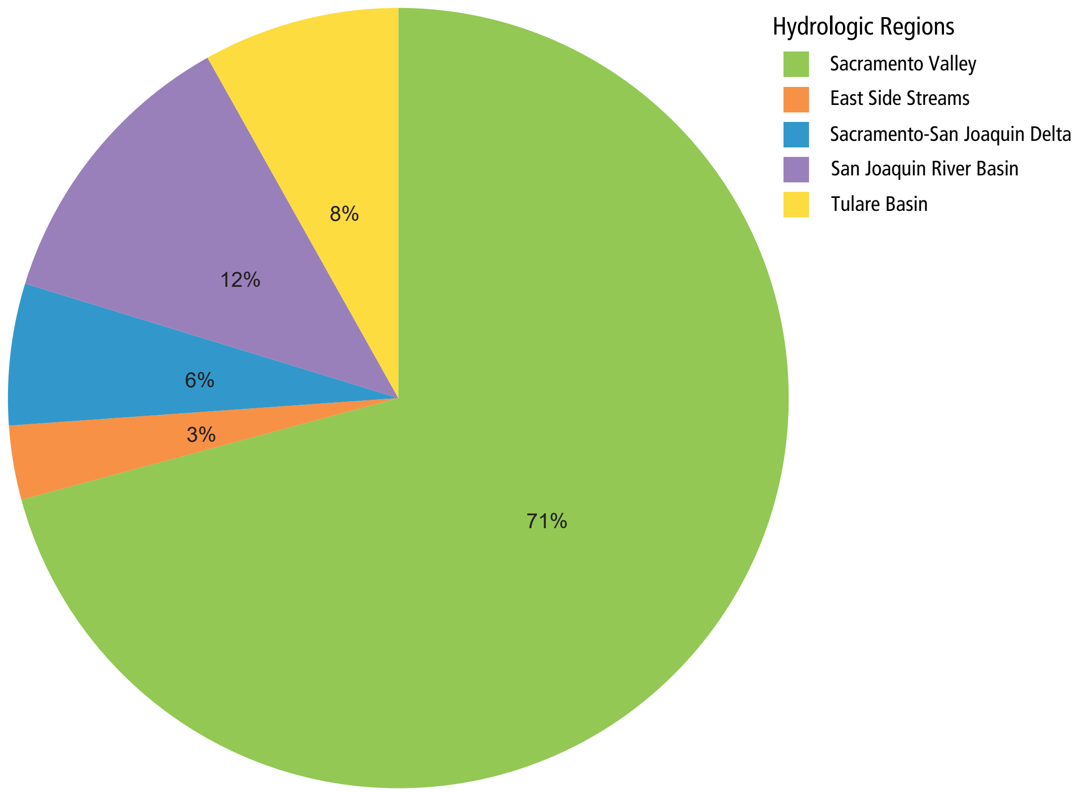


Figure 33. Regional distribution of surface-water inows from small-stream watersheds, water years 1922-2009.



The Groundwater Flow Process Reports

The Groundwater Flow Process models water movement into, through and out of the Central Valley aquifer, including the unsaturated and saturated portions of the aquifer. The basic C2VSim model simulates the aquifer with three horizontal layers, with the Corcoran Clay confining aquiclude between the top and middle layers in some areas. Horizontal and vertical groundwater flow are simulated using the Galerkin finite element method and a quasi-three-dimensional approach utilizing the depth-integrated groundwater flow equation for horizontal flows in each aquifer layer and leakage terms for vertical flow between aquifer layers. The Simulation program writes groundwater information to two files, CVground.bin and CVZB.bin, which are used by the Budget and Z-Budget programs, respectively.

Groundwater Budget

The Groundwater Budget is produced from information stored in the binary file CVground.bin created by the Simulation program at run-time and is output to the file CVground.BUD. The Groundwater Budget information is reported by subregion, with 21 subregional tables followed by a table labeled 'subregion 22', which reports values for the entire model area. All budget columns are in volumetric units except those related to time and area.

The Groundwater Budget has 16 columns in each subregional budget table. Column 1 contains the time step, column 2 contains deep percolation flowing from the root zone to the unsaturated zone, and columns 3 and 4 contain beginning and ending storage, column 5 contains net deep percolation (from the unsaturated zone to the saturated zone), and columns 6-9 and 11-13 contain flows from other processes. Column 6 contains net flow from (+) and to (-) streams, column 7 contains recharge to the aquifer from injection wells and recoverable losses from diversions and bypasses, column 8 contains net flows from (+) and to (-) lakes, and column 9 contains subsurface inflows from small-stream watersheds. Column 10 contains the net flow released to aquifer storage from subsidence (+) or flowing from aquifer storage to subsidence recovery (-). Column 11 contains inflow from subsurface irrigation, column 12 contains outflow to tile drains, and column 13 contains groundwater pumping. Column 14 contains net subsurface flow into (+) or out of (-) the subregion from or to adjacent subregions. Column 15 contains the mass balance error for the time step, and column 16 contains the cumulative volume of groundwater storage lost to subsidence.

Z-Budget Output

The IWFM Z-Budget program output file contains one table for each of the zones described in the main input file. The exact configuration of these tables will depend on the zonal configuration, the active components included in the model, and the number of zones bordering each zone. Each table has the date in the left-most column, followed by columns containing a consistent set of paired values (inflow and outflow) for specific flow components for the active flow processes affecting the groundwater system, followed by a series of columns detailing subsurface flows between adjacent zones. The Z-Budget program dynamically determines the total number of columns in the output table based on the active flow processes in the model, and then creates inflow and outflow columns for each process that is active in at least one of the zones and layers, and for the adjacent zones. The active flow components in the Z-Budget output file for C2VSim are groundwater storage, streams, tile drains, subsidence, net deep percolation, small-stream watershed baseflow, small-stream watershed deep percolation, recoverable losses from diversions, recoverable losses from bypasses, lakes, elemental pumping (agricultural pumping in the C2VSim model) and well pumping (urban pumping in the C2VSim model). Additional columns detail subsurface inflows and outflows for adjacent subregions.

The Z-Budget program creates two output files each time it is run. ZBudgetMessages.out reports the total run time for a successful run, or any errors for an aborted run. A file with the same root as the input binary file and the 'bud' extension, CVZB.bud, contains budget tables with the run results. When Z-Budget is used with multiple input files delineating different zone configurations, it is generally good practice to rename the Z-Budget output file with the same root as the Z-Budget input file. The Z-Budget Examples section below describes seven Z-Budget input files used with the basic C2VSmi model, and the resulting budget tables.

Groundwater Budget Examples

The data in figures 34-37 was created by running the Budget program using an MPRINT value of 12 in the file CVBudget.in. The annual change in groundwater storage was calculated as the difference between the values in columns 3 and 4, the beginning and ending storage values, from the 'subregion 22' table. The time series of annual values is displayed in figure 34, and the cumulative change in storage for water years 2000 through 2009 is shown in figure 35. The change in storage was calculated for each hydrologic region was calculated by summing the values for subregions 1-7 (HR 1), subregion 8 (HR 2), subregion 9 (HR 3), subregions 10-13 (HR 4), and subregions 14-21 (HR 5). The averages for water years 1922-2009 and 2000-2009 were then calculated for figures 36 and 37.

Figure 34. Simulated annual change in groundwater storage in California's Central Valley for water years 1922-2009.

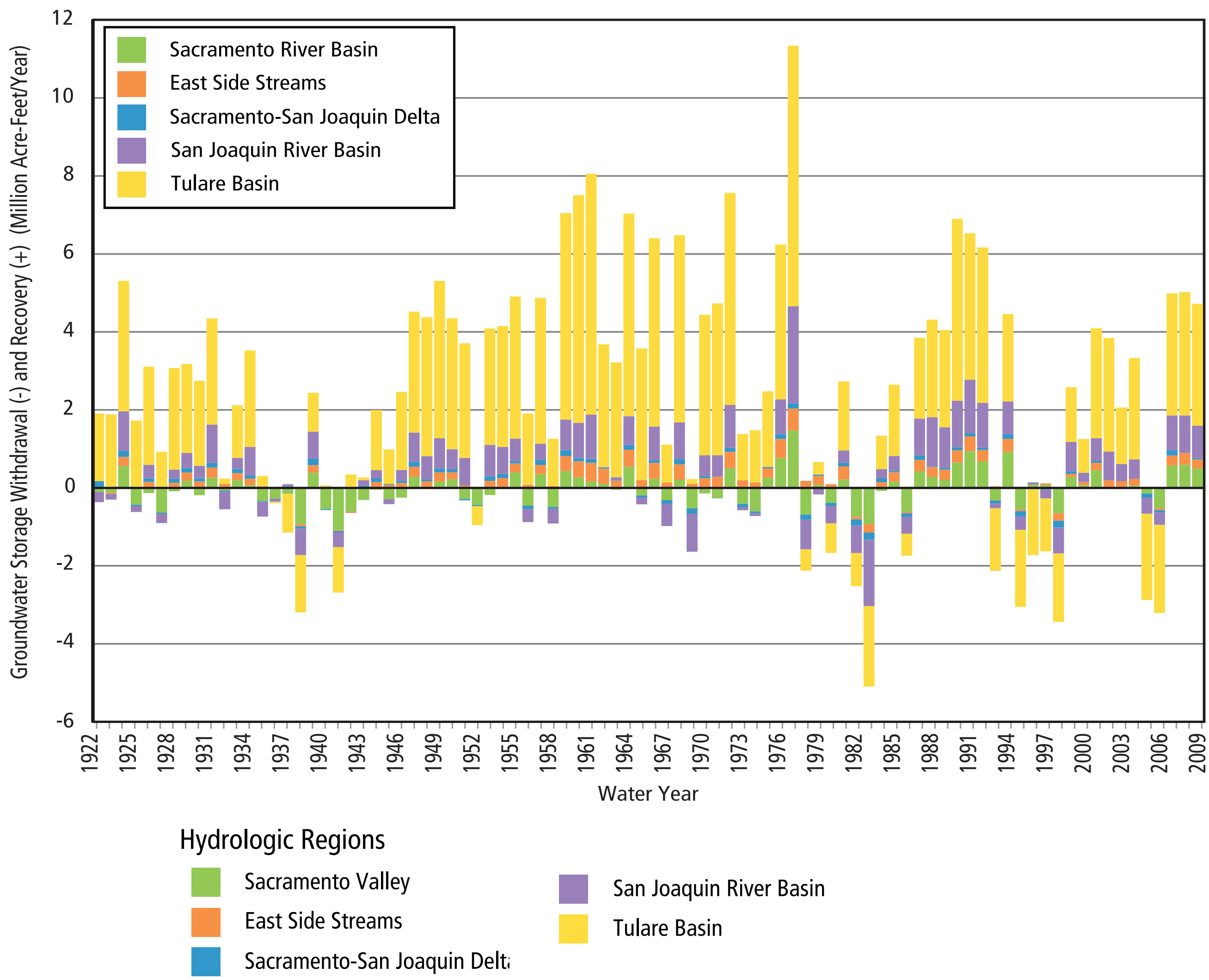


Figure 35. Simulated cummulative change in groundwater storage in California's Central Valley for water years 1922-2009.

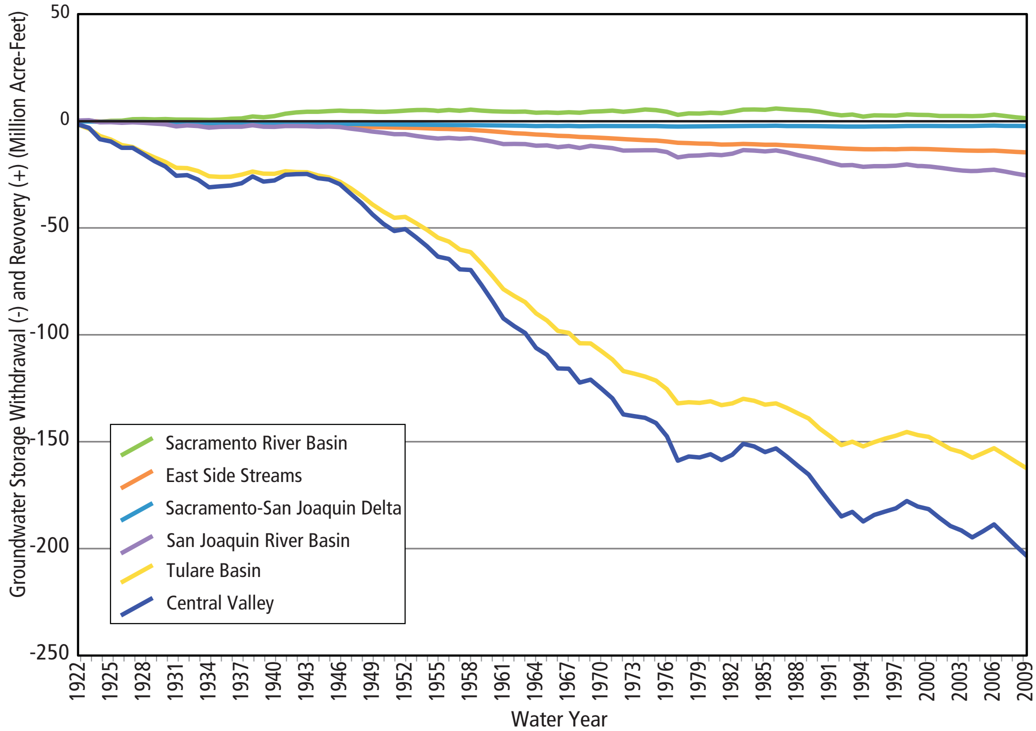


Figure 36. Simulated regional distribution of the change in groundwater storage for water years 1922-2009.

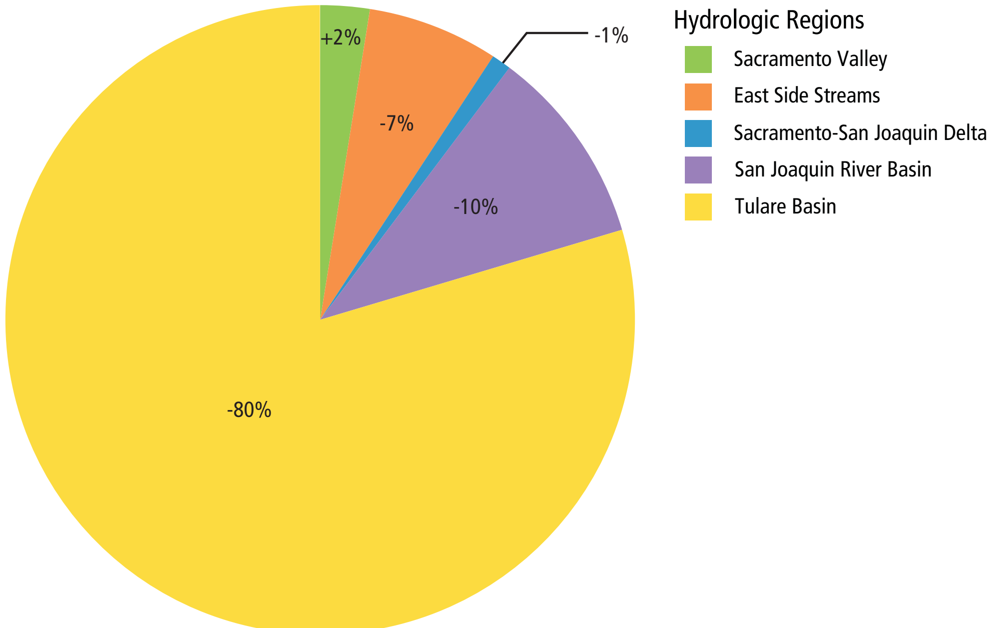
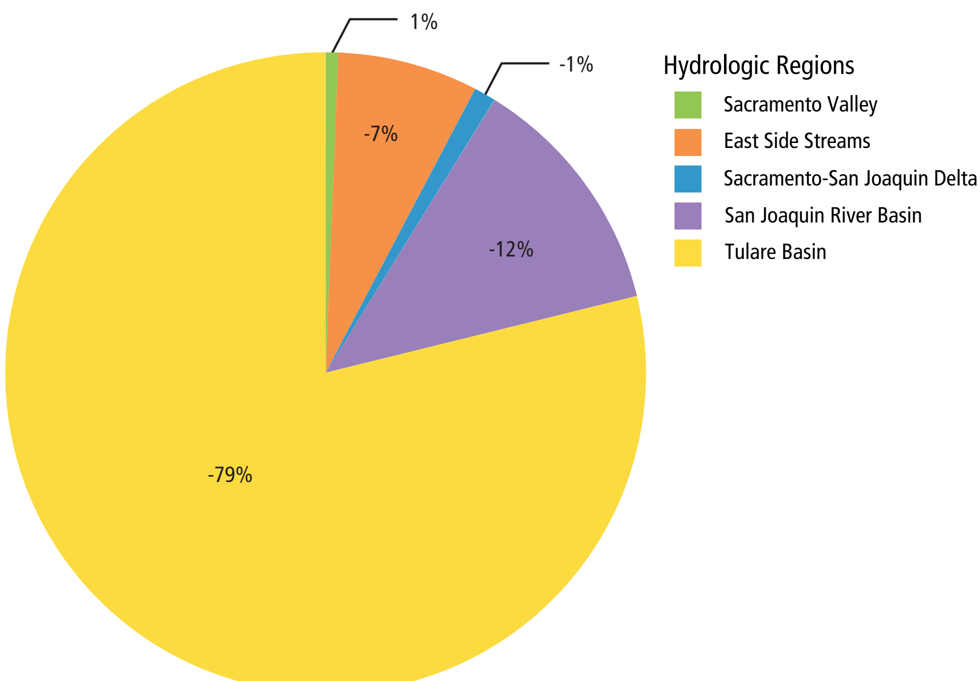


Figure 37. Simulated regional distribution of the change in groundwater storage for water years 2000-2009.



Z-Budget Examples

The Z-Budget program can be used to summarize groundwater information for many different zonal configurations using the CVZB.bin file from a single C2VSim run. Example output from several general zonal configurations are presented here. The Z-Budget report zbudget_all.bud, created by running Z-Budget with the input file zbudget_all.in, provides information on the entire aquifer. Figure 38 uses the separate columns 'Pumping by Element' and 'Pumping by Well', which represent agricultural and urban pumping, respectively, in C2VSim.

Figure 39 used the inflows and outflow for each hydrologic region from the file zbudget_HRs.bud, created by running Z-Budget with the input file zbudget_HRs.in.

Figure 40 shows the inflow and outflow components of the groundwater flow system for water years 2000-2009, taken from the 'subregion 22' table of the file zbudget_SRs.bud, created by running Z-Budget with the input file zbudget_SRs.in.

Figure 38. Simulated agricultural and urban groundwater pumping in California's Central Valley for water years 1922-2009.

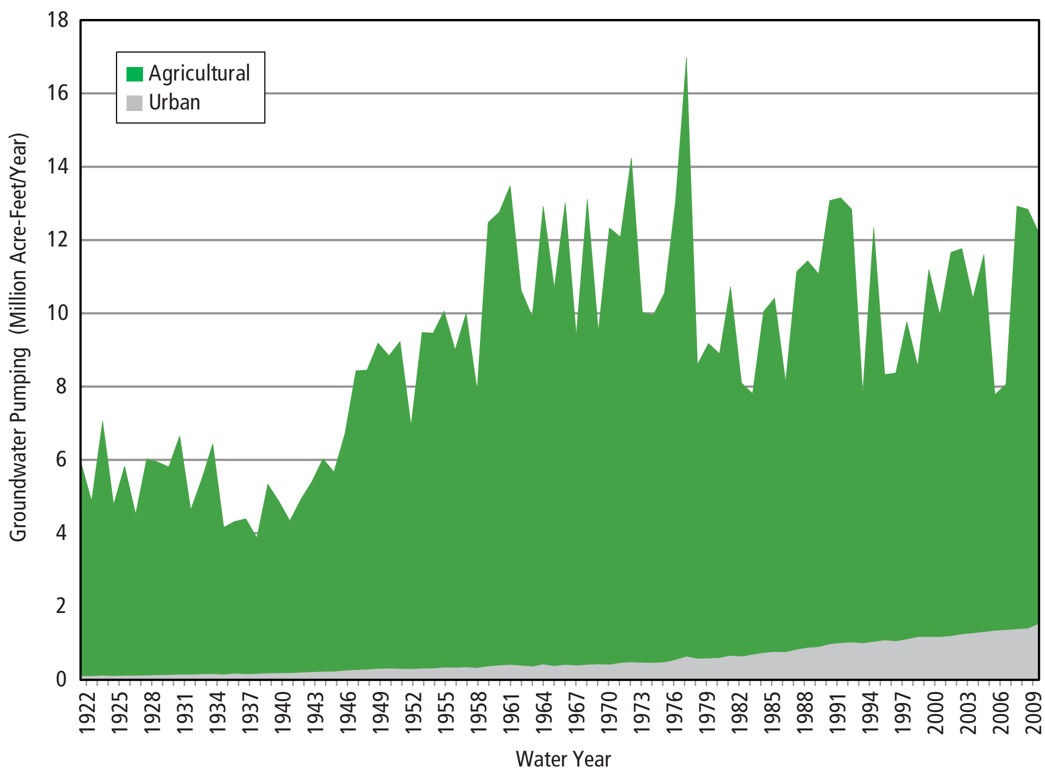
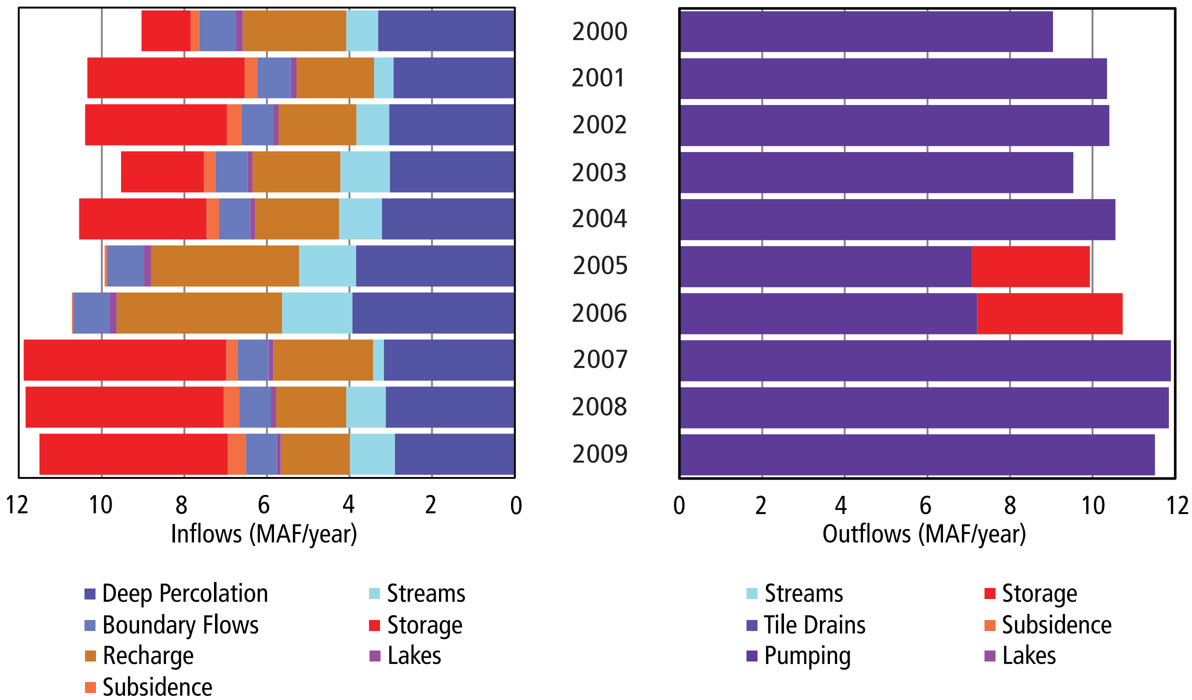


Figure 39. Simulated net annual subsurface ows between hydrologic regions for water years 2000-2009. [Million acre-feet per year]

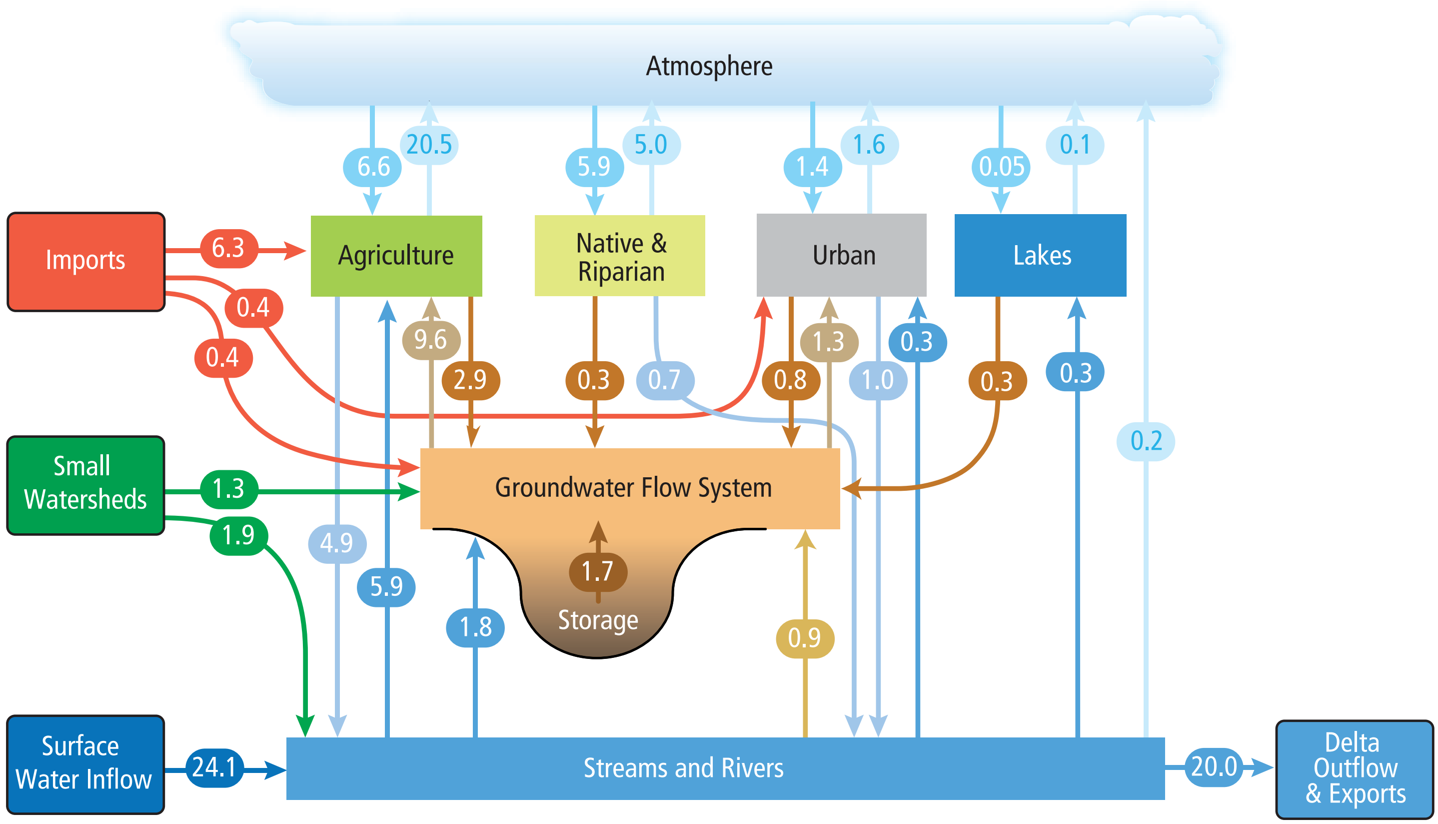
Figure 40. Simulated inows to and outows from California's Central Valley groundwater ow system for water years 2000-2009.



Water Budgets – Combining Output from Multiple Processes

Information from multiple Budget and Z-Budget output files can be combined to generate a water budget flow chart. Figure 41 combines output from the Root Zone Budget, Land and Water Use Budget, Streamflow Budget, Diversion Details Budget, Lake Budget and Groundwater Budget.

Figure 41. Simulated average annual water budget for California's Central Valley for water years 2000-2009.



Average Flows for water years 2000-2009 [Million Acre-Feet/Year]

Generating TecPlotTM Figures

The IWFM Simulation program can optionally produce two files with groundwater head and land-surface subsidence at each model node and layer that are easily read by the graphical program TecPlotTM. The file CVGWheadTecPlot.out holds groundwater heads and the file CVSubsidTecPlot.out holds land-surface subsidence values. These files can be read by the TecPlot program, and used to produce 'movies' of groundwater heads and subsidence through time.

References

Berkstresser, C. F., Jr. 1973. Map showing base of fresh ground-water, approximately 3,000 micromhos, in the Sacramento Valley and Sacramento-San Joaquin Delta, California. Sacramento, CA: U.S. Geological Survey Water-Resources Investigations Report 40-73.

Boyle Engineering Corporation. 1987. Central Valley Groundwater Simulation Model. Sacramento, CA: Boyle Engineering Corporation unpublished model.

Bryan, Kirk. 1923. Geology and ground water resources of Sacramento Valley, California. Washington, DC: U.S. Geological Survey Water-Supply Paper 495.

California Department of Public Works. Undated. San Joaquin Valley water-table map for 1921. Sacramento, CA: California Department of Public Works.

California Department of Water Resources (DWR). 1975. Vegetative water use in California, 1974. Sacramento, CA: California Department of Water Resources Bulletin 113-3.

California Department of Water Resources (DWR). 1986. Crop water use in California. Sacramento, CA: California Department of Water Resources Bulletin 113-4.

CH2M Hill, Inc., and S. S. Papadopoulos and Associates. 2005. Linkage of PEST and IGSM2: Central Valley Model Application. Oakland, CA: CH2MHill Technical Memorandum.

CH2M Hill, Inc., and S. S. Papadopoulos and Associates. 2006. Phase 2: Refine Conceptual Model. Oakland, CA: CH2MHill Technical Memorandum.

CH2M Hill, Inc. 1996. Draft report on model data update, CVGSM study area. Sacramento, CA: CH2M Hill, Inc. Technical Memorandum.

Dogrul, E. C. 2005. Supplemental program for IWFM for Interpolating/Extrapolating Land Survey Data. Sacramento, CA: California Department of Water Resources Technical Memorandum. http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/SupportTools/index_SupportTools.cfm [Accessed October 7, 2011].

Dogrul, E. C. 2007A. Integrated Water Flow Model (IWFM v3.0) Theoretical Documentation. Sacramento, CA: California Department of Water Resources.

Dogrul, E. C. 2007B. Integrated Water Flow Model (IWFM v3.0) User's Manual. Sacramento, CA: California Department of Water Resources.

Dogrul, E. C. 2007C. Z-Budget: Sub-domain Water Budgeting Post-Processor for IWFM, Theoretical Documentation and User's Manual. Sacramento, CA: California Department of Water Resources.

Doherty, John. 2004. PEST – Model-Independent Parameter Estimation User's Manual, 5th edition. Brisbane, Australia: Watermark Numerical Computing.

James M. Montgomery Consulting Engineers. 1990A. Documentation and User's Manual for Integrated Groundwater and Surface Water Model. Sacramento, CA: James M. Montgomery Consulting Engineers, Inc.

James M. Montgomery Consulting Engineers. 1990B. Central Valley Ground-Surface Water Model, Central Valley, California. Sacramento, CA: James M. Montgomery Consulting Engineers, Inc.

Kings River Water Association. 2009. Watermaster Report, Kings River and Pine Flat Reservoir Operation, Administration and Canal Diversion. Fresno, CA: Kings River Water Association.

Mendenhall, W. C., Dole, R. B., and Stabler, Herman. 1916. Ground water in San Joaquin Valley, California. Washington, DC: U.S. Geological Survey Water-Supply Paper 398p.

Page, R. W. 1973. Base of fresh ground water (approximately 3,000 micromhos) in the San Joaquin Valley, California. Sacramento, CA: U.S. Geological Survey Hydrologic Investigations Atlas HA-489.

Taghavi, A., and S. Najmus. 2000. IGSM 5.0 with Upgrade to the Application of the Central Valley Ground and Surface water Model (CVGSM), Technical Memorandum prepared for DWR. Sacramento, CA: Water Resources and Information Management Engineering, Inc.

Tecplot, Inc. 2011. Tecplot 360 2011. http://www.tecplot.com, Bellevue, WA, U. S. A. [Accessed October 5, 2011].

U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC). 2011. HEC-DSS. http://www.hec.usace.army.mil/software/hec-dss/hecdss-dss.html, Davis, CA, U.S.A. [Accessed October 6, 2011].

U.S. Bureau of Reclamation. 1999. Central Valley Project Improvement Act Final Programmatic Environmental Impact Statement. Sacramento, CA: U.S. Bureau of Reclamation.

U.S. Department of Agriculture. 1986. Urban Hydrology for Small Watersheds. Technical Release no, 55. Washington, DC: U.S.D.A. Natural Resources Conservation Service.

U.S. Department of Agriculture. 1997. State Soil Geographic (STATSGO) Data Base. Washington, DC: U.S.D.A. Natural Resources Conservation Service.

U.S. Department of Agriculture. 2004A. Part 630, Hydrology, chapters 9-10. National Engineering Handbook. Washington, DC: U.S.D.A. Natural Resource Conservation Service.

U.S. Department of Agriculture. 2004B. Soil Survey Geographic (SSURGO) database. Washington, DC: U.S.D.A. Natural Resource Conservation Service.

U.S. Geological Survey. 2007. National Hydrography Dataset. Reston, VA: US Geological Survey. http://nhd.usgs.gov, accessed June 10, 2007.

Williamson, A. K., David E. Prudic, and Lindsay A. Swain. 1989. Ground-water flow in the Central Valley, California. Washington, DC: U.S. Geological Survey Professional Paper 1401-D.

Williamson, A. K., David E. Prudic, and Lindsay A. Swain. 1985. Ground-water flow in the Central Valley, California. Sacramento, CA: U.S. Geological Survey Open-File Report 85-345.