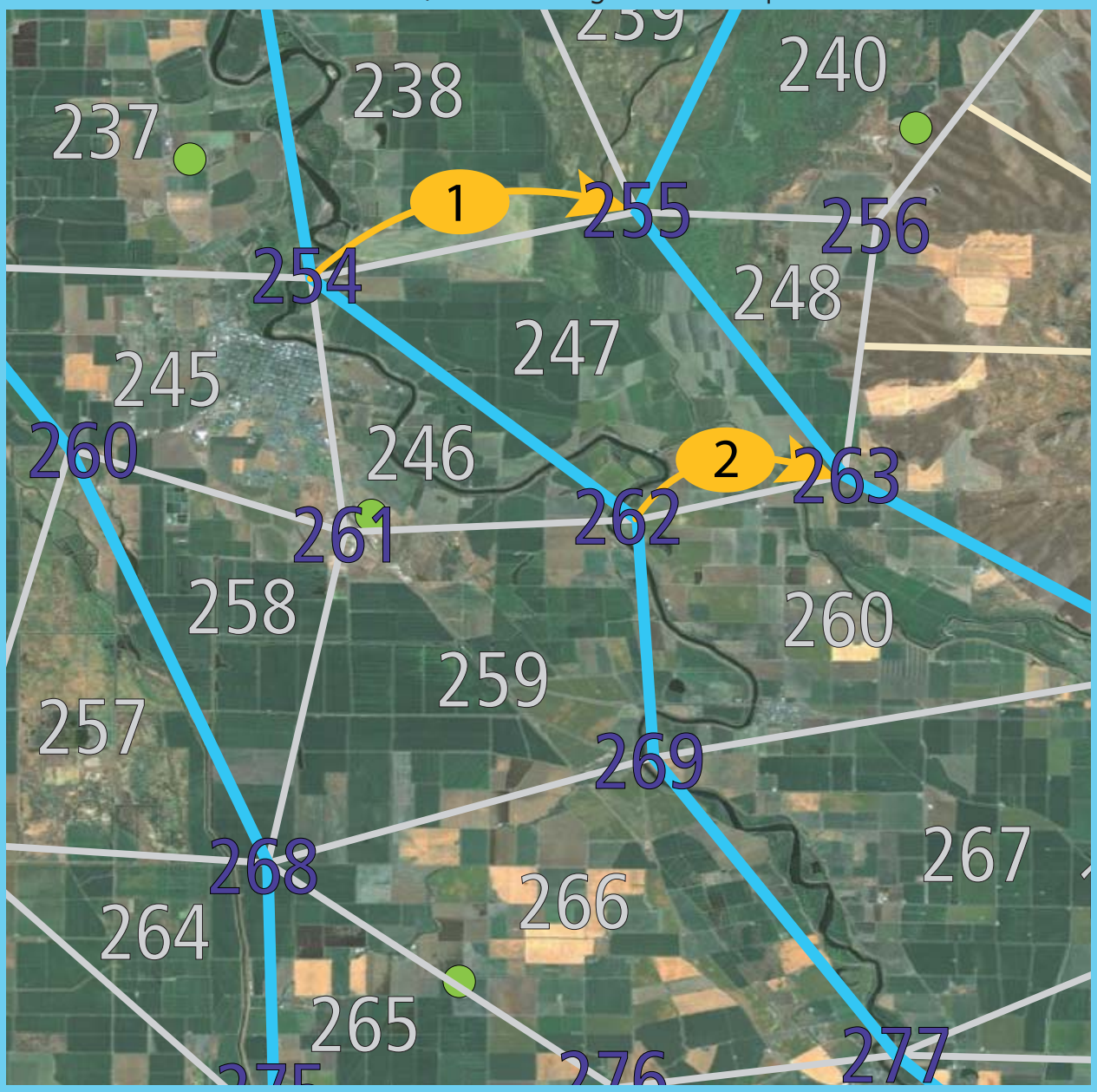
SJC-232

DWR Technical Memorandum

Development and Calibration of the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG

Charles F. Brush, Emin C. Dogrul and Tariq N. Kadir



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

C2VSim-CG Version R374, released June 2013

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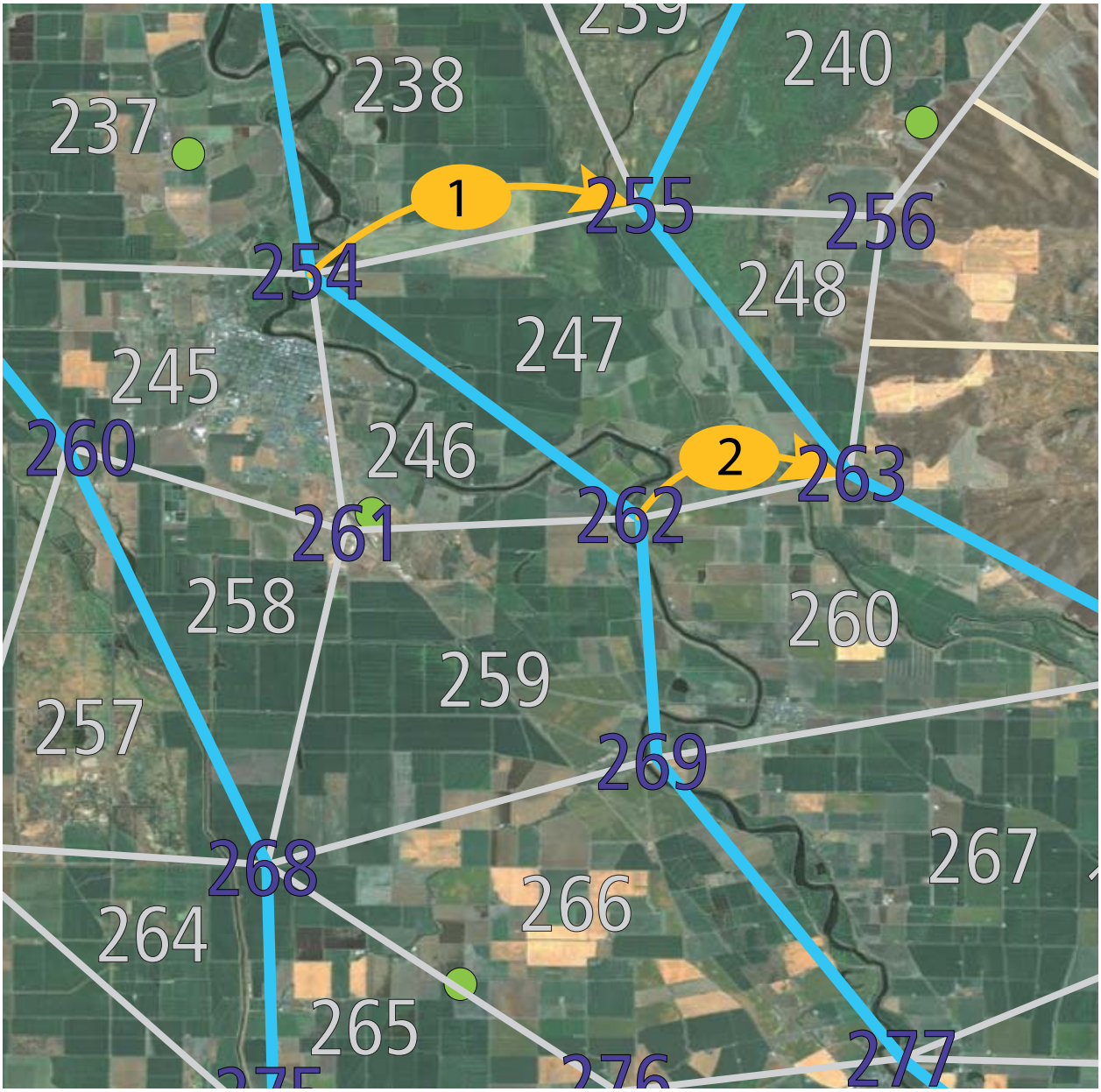

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DWR Technical Memorandum: Development and Calibration the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG
Authors: Charles F. Brush, Emin C. Dogrul, Tariq N. Kadir
Modeling software and documentation originated 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.

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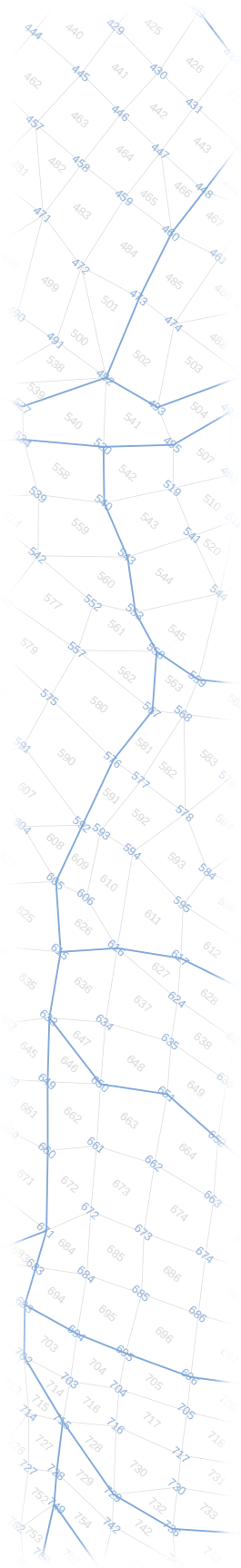
Acronyms and Abbreviations

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

Executive Summary

The population in California's Central Valley has grown from 732,000 people in 1920 to nearly eight million people in 2010, and is projected to grow to more than 11 million people by 2050. During this time, the annual value of Central Valley agricultural products grew to more than $21 billion. The Central Valley is also the hub of the State's water supply system. An extensive network of dams and canals supplies surface water to users within the Central Valley and in the San Francisco Bay Area, Central Coast and Southern California. Agricultural and urban users within the Central Valley consumed on average 13 million acre-feet of surface water and more than eight million acre-feet of groundwater per year between 2000 and 2009, and up to an additional two million acre feet of water were exported to areas outside the Central Valley.

The availability of surface water supplies varies significantly from year to year, and several dry years can result in critically low water reserves. The availability of surface water supplies is also constrained by regulatory restrictions including downstream water rights, in-stream flow requirements on select river reaches and outflow requirements for the Sacramento-San Joaquin Delta. Groundwater is often used as a buffer when surface water supplies are reduced, but over-reliance on groundwater can have serious negative consequences including declining water levels, reduced water quality and land subsidence. Future climatic conditions in the watersheds surrounding the Central Valley are also expected to affect hydrology and water resources management. For example, the volume of water stored in the Sierra Nevada snowpack each spring has declined by about 10 percent in the last century, and is expected to decline further. The water management community is developing planning tools to cope with these increased demands and increased uncertainty in supplies.

The California Department of Water Resources (DWR) has developed the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), an integrated hydrologic model, as a tool to aid in water management planning. C2VSim simulates water movement through the interconnected land surface, surface water and groundwater flow systems in the 20,000 mi^2 (51,000 km^2) area defined by the alluvial Central Valley aquifer. The model uses a detailed database of monthly precipitation, land use, crop acreage, river inflow and surface water diversion information from October 1921 through September 2009 to calculate historical water use, groundwater pumping and changes in aquifer storage.

C2VSim simulates the historical response of the Central Valley's groundwater and surface water flow systems to historical stresses, and can also be used to simulate the effects of projected future stresses. The model will be useful for addressing several key water management questions in the Central Valley. C2VSim can be used to estimate groundwater pumping rates, which are not measured or reported in the Central Valley. The model can also be used to understand water flows between rivers and groundwater aquifers, which are essential for evaluating the impacts of many

conjunctive use and water transfer programs. The C2VSim model is also the basis for the groundwater component of CalSim 3, a water resources planning model for simulating operation of the California State Water Project and Federal Central Valley Project developed in conjunction with the U.S. Bureau of Reclamation.

C2VSim was developed using the California Department of Water Resources' Integrated Water Flow Model (IWFM) application. IWFM couples a three-dimensional finite element groundwater simulation process with one-dimensional land surface, river, lake, unsaturated zone and small-stream watershed processes. C2VSim dynamically calculates crop water demands, allocates contributions from precipitation, soil moisture and surface water diversions, and calculates the amount of groundwater pumping required to meet the remaining demand. Model input was compiled from California Department of Water Resources' extensive Central Valley land and water use data, which has been continuously collected since 1921.

The C2VSim model output can be summarized to produce water budgets for each of 21 model subregions, five hydrologic regions or the entire model area. Model results show that annual agricultural water demands increased from less than 6 million acre-feet (MAF) in the 1920s to more than 14 MAF by the 1960s, remaining there through the 2000s, and annual urban water demands increased more than ten-fold from less than 0.2 MAF in the 1920s to more than 2 MAF in the 2000s. The surface water delivery volume is greater than the groundwater pumping volume in all but the driest years. Surface water deliveries peaked at more than 16 MAF in 1980, and were greater than 14 MAF/yr for 17 of the 40 years from 1970 to 2009. Groundwater pumping rose in years of surface water shortages, generally fluctuating between approximately 7 and 12 MAF/yr, and peaking at 15 MAF in the 1977 drought. Between 1921 and 2009, groundwater withdrawal exceeded replenishment by nearly 130 MAF, causing the water table to drop as much as 200 ft in some parts of the Central Valley, and causing land-surface subsidence in several areas. Lowering of the water table and changes in river flow rates have also reduced groundwater discharges to rivers, reducing summer flows with resulting increases in water temperatures and declines in water quality.

Introduction

The Central Valley is the centerpiece of California's water supply system. Precipitation falling in the surrounding mountains is captured in reservoirs and routed through river channels and canals to serve users in the Central Valley, and in the San Francisco Bay Area, Central Coast and Southern California. Annual surface water and groundwater usage within the Central Valley has grown from 10 MAF in the 1920s to 21 MAF in the 2000s. Between 1920 and 2010, the Central Valley population grew from 732,000 to nearly 8 million people (CDOF, 2011), and it is projected to grow to more than 11 million people by 2050 (CDOF, 2012). Meanwhile, the annual value of Central Valley agricultural products was more than $21 billion in 2009 (USDA, 2011A).

The California Central Valley Groundwater–Surface Water Simulation Model (C2VSim) is an integrated hydrologic model. C2VSim simulates the movement of water through the linked land surface, groundwater and surface water flow systems in the 20,000 mi^2 (51,000 km^2) area defined by the alluvial Central Valley aquifer. C2VSim was developed using the Integrated Water Flow Model (IWFM) application, an open source software package that couples a three-dimensional finite element groundwater flow simulation process with one-dimensional land surface, stream flow, lake, unsaturated zone and small-stream watershed processes.

The Central Valley hydrologic system has undergone significant changes during the last 100 years as large areas of native vegetation were converted to agricultural and urban use. The climate is characterized by wet winters and dry summers, and this development was accompanied by extensive alteration of the hydrologic system as irrigation water was applied to these areas. Many rivers were dammed, an extensive system of canals was built to distribute the water to farms, and large volumes of water were transferred between hydrologic basins. Large volumes of groundwater were also pumped from the ground, altering stream-groundwater flows and in some cases causing subsidence of the land surface. Each component of this complex water collection and delivery system was designed to meet the water demands at the time it was built. Hydrologic conditions and water demands throughout the Central Valley are much different today than when most of California's water collection and distribution systems were constructed, and upgrades have not kept pace with changing conditions, especially the growing population.

The Central Valley hydrologic system incorporates water movement through many linked flow paths, which can be roughly grouped into the Land Surface Process, Surface Water Flow Process and Groundwater Flow Process. These processes are linked by natural water flow paths including precipitation, runoff, deep percolation and stream-aquifer flows, and what can be described as anthropogenic flow paths including surface water diversions, groundwater pumping, irrigation return flows and urban wastewater discharges. Major inflows to the Central Valley include precipitation and surface water flows from the surrounding watersheds, and surface water imports from the Trinity River watershed. Major outflows

include evapotranspiration, surface water flows through the Carquinez Strait to San Francisco Bay and the Pacific Ocean, and surface water exports to the San Francisco Bay Area and Southern California. For many years, water outflows have exceeded inflows, resulting in a net reduction in groundwater storage, and several groundwater basins within the Central Valley have suffered from overdraft (DWR, 2003).

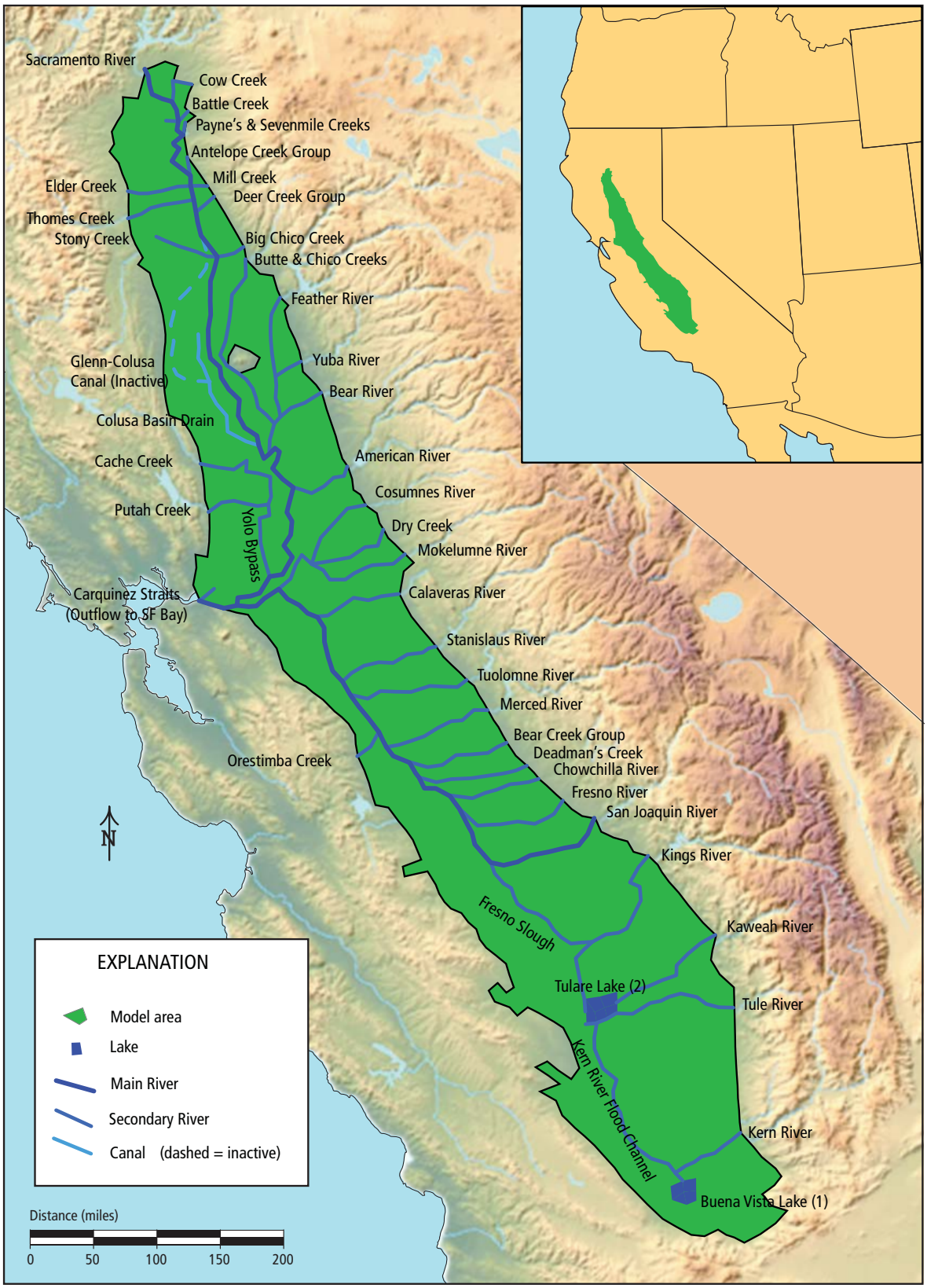
The linkage between groundwater and surface water is a key component of the Central Valley hydrologic system. Historically, groundwater was recharged from streams near where they enter the Central Valley, and groundwater inflows near the Central Valley trough were an important flow component for some rivers, maintaining summer base flows and moderating water temperatures. Flows between groundwater and surface water have changed dramatically as a result of changes in seasonal river flow rates caused by the construction of reservoirs on major rivers, and changes in groundwater levels as a result of widespread groundwater pumping. In recent years, flow rates in many Central Valley rivers and streams have sometimes fallen below the minimum levels required to maintain and restore aquatic and riparian ecosystems (DWR, 2009).

The Central Valley's surface water collection, storage and delivery system is large and complex, and includes more than 1,200 reservoirs and numerous canals, pumps, treatment plants and levees. This integrated system is operated and maintained through a system of decentralized governance which requires a great deal of cooperation among many local, regional, state, federal and tribal entities. This water collection and delivery system must be managed to accommodate changing societal values, environmental constraints, regulations, and future challenges accompanying expected climate change and future population growth. These challenges are more pronounced during droughts, as the effects increase with the length and severity of the drought as water supplies in reservoirs are depleted and groundwater levels decline (DWR, 2009). The Sacramento-San Joaquin Delta, the hub of the state's water supply and delivery system, faces serious ecosystem issues that may affect water deliveries throughout the Central Valley watershed.

The cooperation among the diverse entities that manage the Central Valley water system has been institutionalized in the form of coordinated efforts loosely called integrated regional water management planning. Experience has shown that coordinated management and planning is most effective when common analytical approaches and tools and common data sets are used. The movement toward integrated water management has increased the desire to integrate water management information and objectives, including the use of common data and modeling protocols (DWR, 2009). The use of shared data and tools can improve communication between stakeholders and allow the development of better models, better documentation, easier professional and public access, more transparency, and thus increased confidence in models and modeling studies (CWEMF, 2000).

An integrated hydrologic model can help realize many of these objectives by serving as a repository of shared data and a unified tool set for investigating the effects of proposed management changes. The model input files, with proper

Figure 1. Location of the C2VSim model.



documentation, can serve as a database of historical information including land use, cropping patterns, surface water inflows and diversions. A set of common base case scenarios developed with this model will allow better comparisons between independent studies. Confidence in the model will be supported by the use of open source software, allowing easy and transparent public access to all model source code and data files. As incremental improvements and refinements are made to the model by individual entities they can be incorporated into the publicly available version of the model. This model will thus become more accurate and more detailed over time, and confidence in the model will grow.

Purpose and Scope

The main goal of this project was to develop an integrated hydrologic model of California's Central Valley that is capable of simulating water flows through the distributed land surface, surface water, groundwater and stream-aquifer flows on a continuous basis. The model would be capable of producing regional and subregional water budgets and of estimating groundwater pumping rates. The model would also be capable of being dynamically linked to other models, and of simulating the effects of long-term management strategies and climate change on the Central Valley's hydrologic system. The C2VSim model includes a detailed database of annual distributed land use and crop acreages, surface water inflows and surface water diversions in an easy-to-read textual format. The model was also developed to run on open source and publicly available software, and the model and input database are being documented and made publicly available.

Location of Study Area

The C2VSim model covers the area defined by the Central Valley's alluvial aquifer (Figure 1). The Central Valley is a flat alluvial basin that is roughly 400 miles long and between 20 and 70 miles wide, with an area of approximately 20,000 mi^2 (51,000 km^2). The valley has a single surface water flow outlet at the Carquinez Strait, which connects to San Francisco Bay and the Pacific Ocean. The Central Valley is divided into three large hydrologic regions and two smaller hydrologic regions. The three large regions each comprise approximately a third of the valley: the northern Sacramento River Basin, central San Joaquin River Basin, and the southern Tulare Basin. The Tulare Basin is internally drained, but has historically drained to the San Joaquin River Basin in extraordinarily wet periods, and the Sacramento River Basin and San Joaquin River Basin drain to the Sacramento-San Joaquin Delta. The two small hydrologic regions are located between the Sacramento River Basin and San Joaquin River Basin. The Eastside Streams hydrologic region is located to the west of the Sacramento-San Joaquin Delta, a tidal area that connects to San Francisco Bay.

Model Origin

The C2VSim model is based on the Central Valley Ground-Surface Water Model (CVGSM), an integrated hydrologic model that was run with the IGSM software. The original CVGSM model was developed by James M. Montgomery Consulting Engineers and Boyle Engineering in 1990, and simulated the Central Valley hydrologic system from October 1921 through September 1980. The CVGSM model was updated by CH_2MHill in 1996, and further modified by WRIME Inc. DWR used the IGSM software as the basis of the IWFM software, significantly updating the numerical methods to address concerns raised in a peer review (LaBolle et al., 2003). DWR then converted the CVGSM model to work with the IWFM software as the C2VSim model, reviewed and updated the model input files, and calibrated the resulting model. The resulting model is presented in this report.

The C2VSim finite element grid uses 1,393 nodes to form 1,392 irregular elements covering an area of 19,710 mi^2, and 449 river nodes to delineate 75 river reaches. C2VSim utilizes a detailed database of areal precipitation, surface water inflows and diversions, and land use and crop acreages from October 1921 to September 2009. C2VSim dynamically calculates monthly crop water demands, allocates contributions from precipitation, surface water diversions and soil moisture, and calculates the volume of groundwater pumping required to meet the remaining demand. Groundwater pumping is not monitored in the Central Valley, and the model can be used to generate a robust estimate of the distributed monthly groundwater pumping. Inter-process flows are also balanced to calculate stream-aquifer interaction at each river node and changes in groundwater levels and storage at each groundwater node. The model produces a good match to observed groundwater heads and river flows.

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 and Sushil Arora of DWR, and administrative support was provided by Sina Darabzand and Rich Juricich of DWR and Robert Leaf of CH_2MHill. 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, Dane Mathis, Michael McGinnis, Dan McManus, Paul Mendoza, Chris Montoya, Robert Niblack, Charlie Olivares, Scott Olling, Eric Senter, Steven Springhorn, Kelly Staton, Jean Woods, Brett Wyckoff.

Surface water diversion data were provided by Peter Arpin and Robert Barbato of the U.S. Army Corps of Engineers, Ben Bray of East Bay Municipal Utility District, Andy Draper of MWH Global, Terry Erlewine of the State Water Contractors, Andy Florentino of Solano County Water Agency, Clifton Lollard 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 CH_2MHill 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.

The Central Valley's Water Resources

California's Central Valley is one of the most productive agricultural regions in the world. The total value of California's agricultural production was $33.9 billion in 2007 and 10% of total U.S. farm production, making it the highest value of any U.S. state (USDA, 2011a). Central Valley agricultural products had a market value of approximately $21.1 billion in 2007, or 62% of the state total (USDA, 2011a). California's agricultural exports of $11.3 billion in 2007 were 14% of the U.S. total, the highest of any U.S. state (USDA, 2011b), and many of these products originated on Central Valley farms. Each dollar of agricultural produce is also estimated to produce an additional three dollars of related economic activity (CDFA, 2012).

Much of California's agricultural production occurs in a semi-arid to arid environment, and relies on large quantities of irrigation water. In 2007, approximately 6 million of the 13 million acres of Central Valley farmland were irrigated, 75% of the state's irrigated area (USDA, 2009a). Central Valley farms used 11.4 MAF of surface water and an estimated 10 MAF of groundwater in 2007. This is 94% of the irrigation water used in California and 23% of that used in the United States (USDA, 2009b).

Central Valley municipal and industrial users consumed approximately 2.1 MAF of water in 2007, with approximately two-thirds coming from groundwater. Total Central Valley groundwater use of 11.4 MAF is approximately 13% of total United States groundwater use, making the Central Valley aquifer the second largest source of groundwater in the United States, after the High Plains aquifer (Kenny et al., 2009; Reilly et al., 2008).

Geography

The Central Valley is an elongated trough located between the Sierra Nevada mountains to the east and the California Coast Ranges to the west. These surrounding mountains provide a watershed that supplies large volumes of surface water to the Central Valley. Knowledge of how the Sierra Nevada and the Coast Ranges formed is important to understanding the deposition of aquifer material in the Central Valley and the distribution and movement of groundwater (Bertoldi et al., 1991). The origin, placement and subsequent evolution of the geologic materials comprising the Central Valley aquifer affect their hydrologic properties. For example, sediments derived from source rocks in the Sierra Nevada and Coast Ranges generally have significantly different grain sizes and chemical properties. Glacial cycles have produced a distinct layered formation in the Central Valley aquifer. After deposition, sediments have been further modified by geologic forces including tectonic subsidence and northward migration of the Pacific Plate.

Central Valley Watershed

The California Department of Water Resources divides the State into ten Hydrologic Regions that correspond to the state's major water drainage basins (DWR, 2009).

This report is concerned with the portions of three broadly defined watersheds that drain to and include the floor of the Central Valley: the Tulare Lake, San Joaquin River and Sacramento River Hydrologic Regions (Figure 2).

The Tulare Lake Hydrologic Region covers approximately 17,000 square miles, and drains portions of the southern Sierra Nevada Mountains, the Temblor Range and the Tehachapi Mountains. The Kern, Tule and Kaweah rivers flow into the Central Valley from the east. The area is generally internally drained, with water naturally flowing to Tulare Lake; during extremely wet periods, Tulare Lake has overflowed into the South Fork Kings River, with the outflow travelling from there to the Fresno Slough and San Joaquin River and out to the Pacific Ocean.

The San Joaquin River Hydrologic Region covers approximately 15,200 square miles, draining portions of the central Sierra Nevada Mountains and Coast Ranges and incorporating the southern half of the Sacramento-San Joaquin Delta. The San Joaquin River flows into the valley near Fresno, and then northward to the Sacramento-San Joaquin Delta. Major tributaries include the Kings, Fresno, Chowchilla, Merced, Tuolumne, and Stanislaus rivers.

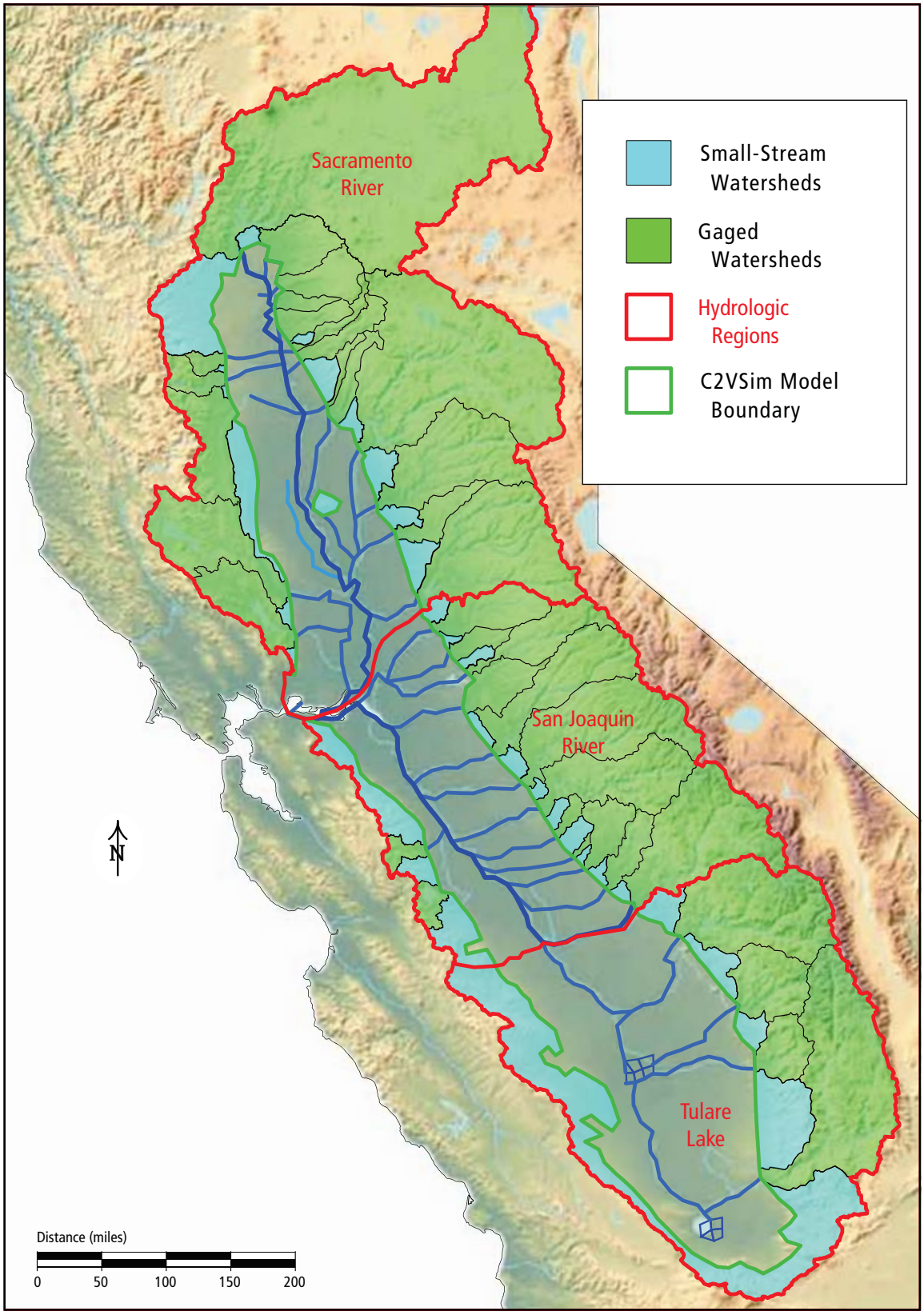
The Sacramento River Hydrologic Region covers approximately 27,200 square miles, extending from Oregon to the Sacramento-San Joaquin Delta. The watershed includes the Modoc Plateau and portions of the Klamath, Cascade, Sierra Nevada and Coast Ranges and the northern half of the Sacramento-San Joaquin Delta. The Sacramento River is the longest river system in California, with major tributaries the Pit, Feather, Yuba, Bear and American rivers. This watershed is the main water supply for much of California's urban and agricultural areas, with annual runoff averaging 22 MAF, nearly one-third of the state's total natural runoff (DWR, 2003).

Hydrologic Regions

The Central Valley floor has been divided into five hydrologic regions to facilitate model development and reporting results (Figure 3, Table 1). From north to south, these are (1) the Sacramento Valley, (2) Eastside Streams, (3) Sacramento-San Joaquin Delta, (4) San Joaquin Basin, and (5) Tulare Basin. The northern Sacramento Valley comprises the area draining to the Sacramento River. The southern Tulare Basin is internally drained, with water historically flowing to the low-lying Kern Lake, Buena Vista Lake and Tulare Lake, which would spill water to the San Joaquin Basin when full. The San Joaquin Basin comprises the area draining to the north-flowing San Joaquin River. The Sacramento-San Joaquin Delta (generally referred to as the Delta in this report), located at the confluence of the Sacramento and San Joaquin Rivers, consists of numerous islands interspersed with river channels, and drains through the Carquinez Strait to San Francisco Bay and the Pacific Ocean. The Eastside Streams region is located to the east of the Delta and includes the Mokelumne and Cosumnes rivers.

The five hydrologic regions are further divided into 21 model subregions (Figure 3, Table 1) for data input and water budget calculations. These subregions were taken directly from the CVGSM model (James M. Montgomery Consulting Engineers,

Figure 2. The California Central Valley watershed.



1990A). The Sacramento Valley region includes subregions 1-7, the Eastside Streams region is subregion 8, the Delta region is subregion 9, the San Joaquin River region is subregions 10-13, and the Tulare Basin region is subregions 14-21. Parameters and input data for the C2VSim model are organized by subregion, and water budgets are calculated for subregions.

Geologic Structure

California's Central Valley is a northwest-trending trough approximately 400 mi (640 km) from north-northwest to south-southeast, with the center axis located toward the steeper western side (Figure 4). The valley is surrounded on all sides by mountains, with a narrow opening in the western side that leads through the Carquinez Strait to San Francisco Bay and the Pacific Ocean. The valley floor overlies the alluvial portion of the Central Valley, and varies in width from approximately 20 mi (30 km) to 70 mi (110 km), with an area of approximately 20,000 mi^2 (52,000 ha^2). The Central Valley receives surface water from mountain watersheds with a total area of approximately 60,716 mi^2 (175,251 km^2).

The basement rock underlying the Central Valley was emplaced in a forearc basin when the Farallones Plate was being subducted beneath the North American Plate, and was significantly modified by the subsequent northward migration of the Mendocino Triple Junction (Lettis and Unruh, 1991). The Central Valley basement materials were emplaced in a forearc basin at the edge of the Pacific Ocrean between 60 and 5 million years ago (Mya). Subduction and subsequent melting at the leading edge of the Farallones Plate also led to the formation of the Sierra batholith. The cessation of subduction followed by the northward migration of the Mendocino Triple Junction caused uplift of the Coast Ranges, creation of the Sierra Nevada mountains through westward tilting of the Sierra batholith, and the creation of a basin between them.

The basin was open to the Pacific Ocean as it formed, but became isolated from the ocean by the rising Coast Ranges. The basin also filled with sediments eroded from the Sierra Nevada and Coast Ranges. The Central Valley basement has continued to subside under the influence of several factors including compression between the Pacific and North American plates, westward tilting of the Sierran block, uplift of the Coast Ranges, and the sediment load. The line of maximum subsidence lies between the western margin of the valley and the north-south axis of the major rivers. Minimum average subsidence rates up to 0.4 m per thousand years (kya) have been proposed (Lettis and Unruh, 1991).

This continued tectonic subsidence is a key factor in the development and character of the Central Valley aquifer. Sediments have been delivered to the basin from the surrounding mountains in a repeating depositional cycle for several million years. This repeating cycle has three phases: (1) descent of the basement and accompanying lowering of the land surface, creating 'accommodation space', (2) filling with eroded sediments produced during the formation and retreat of glaciers, and (3) development of soils on the land surface during interglacial periods

Figure 3. C2VSim model subregions and hydrologic regions.

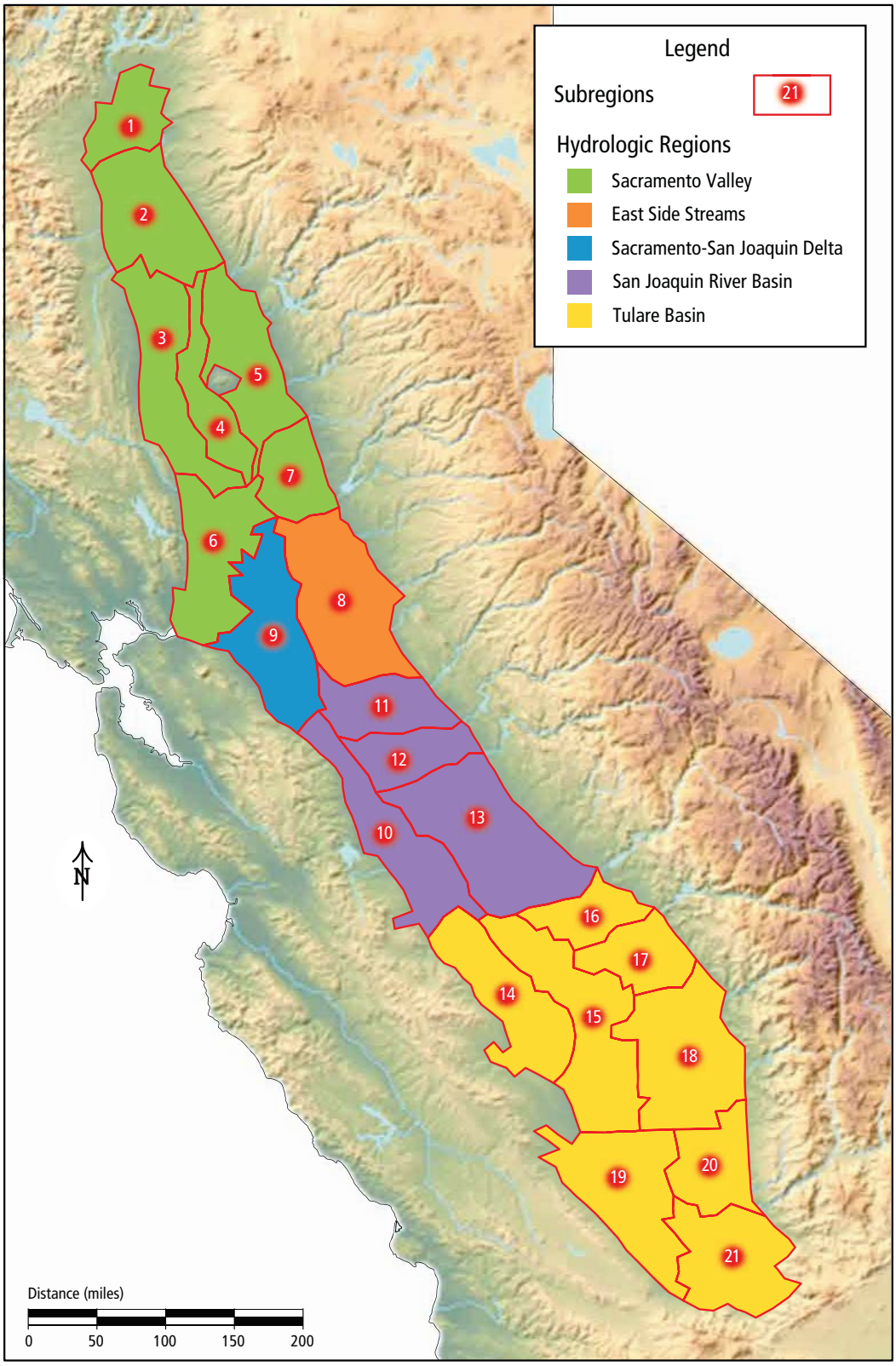


Table 1. C2VSim subregions and hydrologic regions

Hydrologic Region	Subregion	DSA	Model Elements	Area (Ac)	Area (mi2)	Area (km2)	% Area
Sacramento Valley	1	58	46	328,278	513	1,328	3%
	2	10	84	698,014	1,091	2,825	5%
	3	12	79	689,108	1,077	2,789	5%
	4	15	46	351,576	549	1,423	3%
	5	69	77	613,755	959	2,484	5%
	6	65	64	657,863	1,028	2,662	5%
	7	70	46	349,858	547	1,416	3%
		TOTAL	442	3,688,451	5,763	14,927	29%
Eastside Streams	8	59	88	895,534	1,399	3,624	7%
Delta	9	55	78	725,454	1,134	2,936	6%
San Joaquin Basin	10	49A	70	668,072	1,044	2,704	5%
	11	49B	44	412,543	645	1,670	3%
	12	49C	33	340,336	532	1,377	3%
	13	49D	117	1,037,638	1,621	4,199	8%
		TOTAL	264	2,458,589	3,842	9,950	19%
Tulare Basin	14	60A	71	670,229	1,047	2,712	5%
	15	60B	105	847,969	1,325	3,432	7%
	16	60C	31	302,449	473	1,224	2%
	17	60D	39	372,889	583	1,509	3%
	18	60E	90	897,091	1,402	3,630	7%
	19	60F	77	801,420	1,252	3,243	6%
	20	60G	42	423,713	662	1,715	3%
	21	60H	65	615,927	962	2,493	5%
		TOTAL	520	4,931,686	7,706	19,958	39%
		All	1,392	12,699,714	19,843	51,394	

(Lettis and Unruh, 1991; Weissmann et al., 2002A). This cycle produced an aquifer composed of repeating layers of relatively permeable materials and horizontally extensive lenses of poorly conductive clays and silts, which slope downward toward the center of the valley (Lettis and Unruh, 1991; Unruh, 1991; Weissmann et al., 2002A; Verosub et al., 2009).

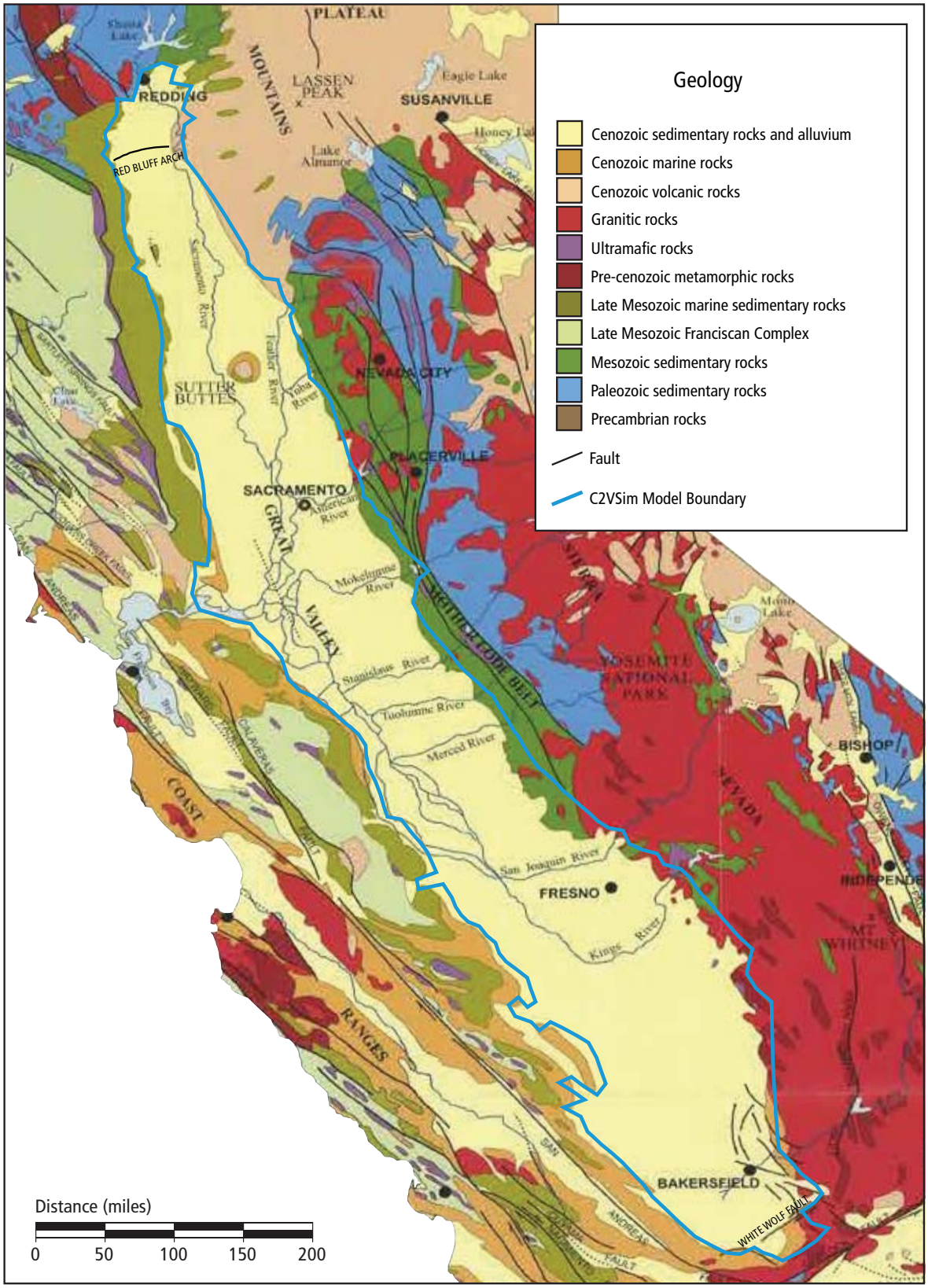
Surface sediments and fresh water aquifers in the Central Valley are generally composed of alluvial fans, stream channel deposits and flood plain deposits (Page, 1986). The aquifer sediments are characterized by the source material (oceanic crust of the Coast Ranges or igneous of the Sierra Nevada), the deposition environment (exposed or submerged), and, for exposed deposition, the climatic conditions (glacial or interglacial). Aquifer sediments on the western side of the Central Valley are

generally derived from oceanic material and are finer grained than the granitic and volcanic sediments on the eastern side of the valley. The Sacramento Valley aquifer contains up to 10 vertical miles (16 km) of sediment, with no extensive confining layers, but some local confined and semi-confined aquifers (Page, 1986). The Tulare Basin contains up to 6 vertical miles (10 km) of sediment (Page, 1986). In the Sacramento-San Joaquin Delta, sediments were removed by extensive river discharges during glacial melting periods, and sediments accumulated during interglacial periods, accompanied by peat accumulation in extensive wetlands. Deep sediments that lie near the basement were generally deposited beneath sea water, and still retain saline water (referred to as conate water). Shallower sediments were generally deposited in exposed (sands and gravels) or submerged fresh water (clays) conditions. Most of the fresh-water aquifers are comprised of post-Eocene continental deposits.

Although the Central Valley sedimentary basins are very thick, the fresh water aquifer in each basin is very thin. The base of fresh water is generally identified by the presence of either relatively impermeable basement rocks or waters with an electrical conductivity less than a specified value. The transition from fresh water to poor-quality water is generally gradual, and thus the location of the fresh water boundary is dependent on how fresh water is defined. Some authors have equated the base of fresh water with the post-Eocene sediments, which were deposited in a fresh-water environment (Bertoldi et al, 1991); however this deposition environment does not always correlate with present day water quality. Both Berkstresser (1973) and Page (1973) defined the base of fresh water in the Central Valley by defining fresh water as water having an electrical conductivity less than 3,000 mhos. Current water quality standards define fresh water as water having an electrical conductivity of 1,500 mhos, so the fresh water boundary defined by Berkstresser (1973) and Page (1973) is probably deeper than what would be delineated using the current water quality standards. Recent work in the Sacramento Valley by DWR staff (Steven Springhorn, unpublished report) has delineated a base of fresh water that is significantly different from that of Berkstresser (1973).

Large lakes that developed during some periods and were later buried beneath alluvial sediments resulted in the formation of extensive clay layers, especially in the San Joaquin and Tulare basins. The most significant, the Corcoran Clay Member of the Tulare Formation, underlies most of the west side of the San Joaquin Valley, and ranges in thickness from near zero up to 160 ft (Page, 1986). The Corcoran Clay is a significant component of the groundwater flow system, and historically acted as a confining unit before numerous wells installed with screens above and below it allowed significant increases in vertical groundwater flow. Numerous local lenses of fine-grained material (silt, sandy silt, sandy clan and clay), which constitute more than half of the total aquifer thickness throughout much of the Central Valley (Page, 1986), significantly restrict vertical flows, and render the aquifer effectively semi-confined to confined within a few hundred feet of the water table in many areas (Williamson et al., 1989). This is demonstrated by significant vertical head differences in many locations.

Figure 4. California Geology



Geologic structures within the Central Valley influence surface water and groundwater movement (Page, 1986). The Sutter Buttes, a small mountain range located in the central part of the Sacramento Valley, obstructs surface water flow and affect the groundwater flow system (Springhorn, 2008). The irregular spatial and temporal pattern of basement subsidence and sediment accumulation reveals numerous structural basins and arches superimposed on the major northwest-trending valley axis (Lettis and Unruh, 1991). The major structural basins in the southern San Joaquin Valley are the Buena Vista and Tulare Basins. The basins are smaller in the northern San Joaquin Valley and Sacramento Valley, with an amplitude of 5 to 40 miles. A series of anticlines are present along the western margin of the Central Valley along the Coast Ranges-Great Valley margin. Prominent anticlines include the Corning Domes, Dunnigan Hills anticline and associated Plainfield Ridge, Montezuma Hills, Panoche Hills, Anticline Ridge, Guijarral Hills, Kettleman Hills, Lost Hills, Elk Hills, Buena Vista Hills and Wheeler Ridge. These anticlines affect the east-west movement of surface water and groundwater, and are associated with faults that may act as barriers to groundwater flow (Olmsted and Davis, 1961; DWR, 1978; Harwood and Helley, 1982; Page, 1986; Faunt et al., 2009).

Faults extending upward from the basement rocks into the alluvium may also act as horizontal barriers to groundwater flow (Page, 1986). The Red Bluff Arch at the northern end of the Sacramento Valley is a group of faults that act as a groundwater flow barrier (Page, 1986). The White Wolf and Edison faults in Kern County also act as horizontal barriers to groundwater flow (Wood and Dale, 1964). Other faults which may act as horizontal barriers to groundwater flow include the Battle Creek Fault, the Corning Fault, and the Willows Fault Zone extending southeast from the Orland Buttes to Sacramento in the Sacramento Valley; the Rio Vista Fault, the Midland Fault, and the roughly collinear Vaca, Potrero Hills, Kirby Hills and Pittsburgh faults extending across the Sacramento-San Joaquin Delta; and the Stockton Fault, Vernalis Fault, Visalia Fault, and Pond-Poso Creek Fault in the San Joaquin Valley.

The Central Valley groundwater flow system comprises a regional aquifer that can be divided into local groundwater basins along geographic and political boundaries to facilitate water management and planning (DWR, 2003). The Central Valley is divided into two large groundwater basins (see Figure 5), the Sacramento Valley Groundwater Basin (5-21), and the San Joaquin Valley Groundwater Basin (5-22). The C2VSim model also covers the Redding Area Basin (5-6) and the Suisun-Fairfield Valley Basin (2-3). These groundwater basins are further divided into sub-basins. These sub-basins are delineated based on political, administrative and surface water boundaries, and may not reflect physical characteristics of the aquifer. The C2VSim model area covers 15 sub-basins of the San Joaquin Valley Groundwater Basin, 15 sub-basins of the Sacramento Valley Groundwater Basin, and five sub-basins of the Redding Area Basin.

Climate

The climate of California's Central Valley varies dramatically both geographically and from month to month and year to year. Precipitation rates are significantly greater

in the northern part of California, with about 70% of California's average annual precipitation falling north of Sacramento. Temperatures and evapotranspiration rates are significantly greater in the south, with about 75% of the state's urban and agricultural water demands occurring to the south of Sacramento. Precipitation is the state's primary water source, and the natural variability in annual precipitation rates produces large annual fluctuations in available water resources.

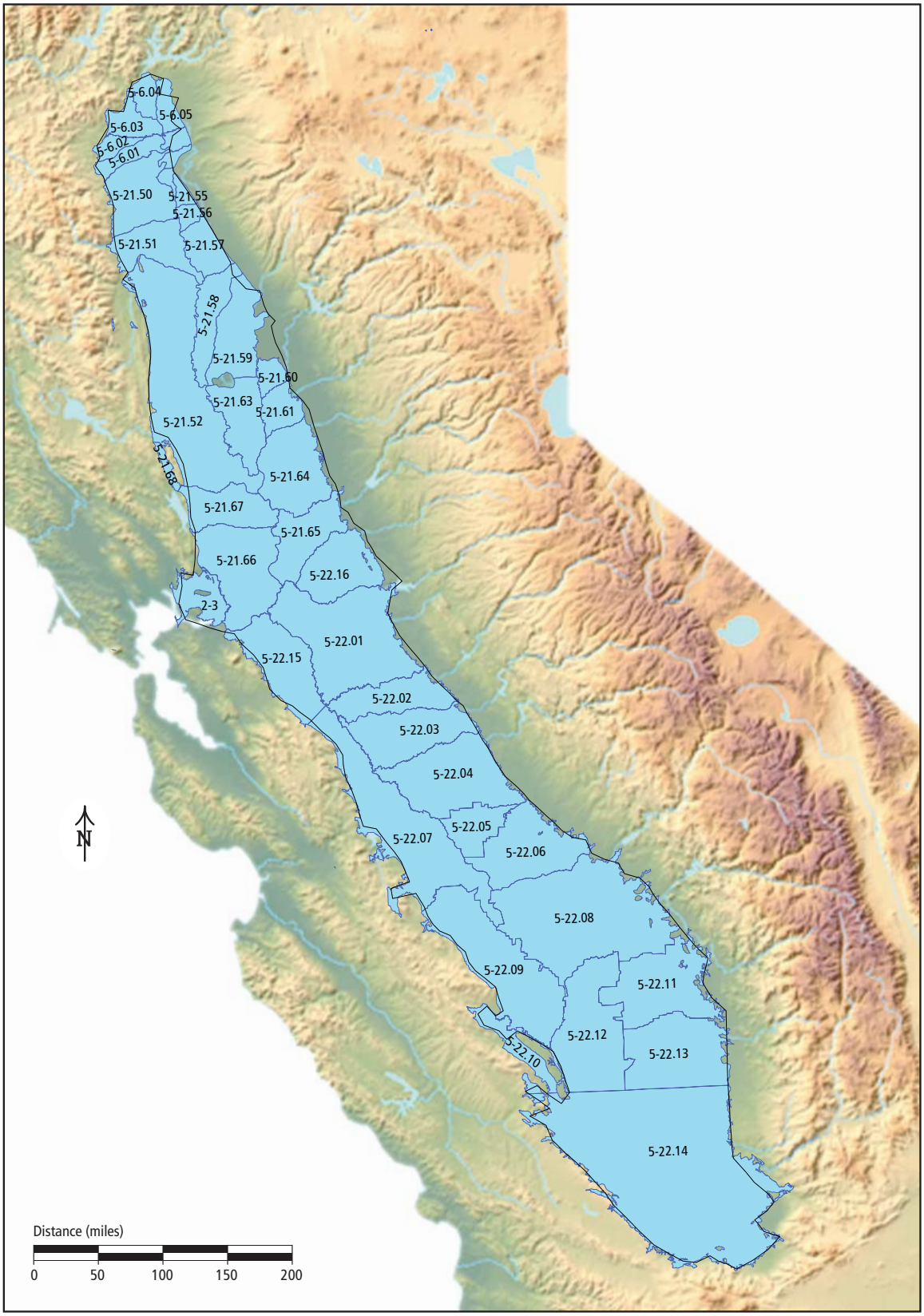
The climate in the Central Valley is characterized by wet winters and dry summers, with most precipitation occurring between the months of November and March, and with the lowest annual precipitation in the southern portion of the valley and highest in the northern part of the valley (Figure 6). Moist air flowing eastward from the Pacific Ocean produces precipitation as it rises in the Coast Ranges, Klamath Mountains, and Sierra Nevada Mountains. The rain shadow produced by the Coast Ranges is also responsible for the dry conditions along the western border of the Central Valley. Winter precipitation in the mountains to the east accumulates as a large snowpack, which melts through the spring and early summer, providing surface water flows that coincide with the irrigation season for agricultural crops. Annual unimpaired surface water flows to the valley from the surrounding mountains have averaged approximately 31 MAF. Approximately 15 MAF of this precipitation accumulates as snowpack, forming the state's largest surface water reservoir.

Central Valley surface water supplies are impacted by both climatic events and administrative constraints, and can fluctuate significantly from year to year. The main climatic constraints are the amount of water stored in the Sierra Nevada snowpack volume each winter, and the amount of holdover storage from precipitation in previous years. Administrative constraints include regulations and court decisions, especially those regarding surface water exports through the Sacramento-San Joaquin Delta (DWR, 2009). Annual fluctuations have been reduced somewhat by the construction of water storage and flood control reservoirs on most of the major tributaries to the Central Valley and the development of large conveyance facilities.

The Sacramento River Index and San Joaquin River Index demonstrate the degree to which surface water availability fluctuates (http://cdec.water.ca.gov/cgi-progs/iodir/wsihist). Each of these indexes is calculated as the weighted sum of spring unimpaired runoff (in million acre-feet per year), winter unimpaired runoff, and the index of the previous year (a proxy for carry-over storage from the previous year). Each index is used to allocate years to one of five classes: wet, above normal, below normal, dry and critical. Graphs of the two indices for water years 1922 to 2009 (Figure 7) demonstrate the large range of the indices, including very wet and very dry years, and that water year types occur in a very random order. The geographical variations in precipitation are also demonstrated by the lack of correlation between the classifications of the two indices.

Water demands also fluctuate from year to year in response to the wetness or dryness of a given year. In very wet years with excessive precipitation, some agricultural and urban landscape demands are met by rainfall and thus the demands for water deliveries are lower. In years with average to below-average precipitation,

Figure 5. California Central Valley Groundwater Basins.



water demands are usually highest. In very dry water years, urban and agricultural water conservation practices, including fallowing, result in reduced water demands (DWR, 2009).

Agricultural and urban water demands are generally met with a combination of surface water and groundwater supplies. The flexible management of groundwater and surface water supplies to meet water demands is referred to as conjunctive use. The exact amount of groundwater used is not known, because groundwater pumping rates are not measured or regulated in California.

On average, groundwater supplies about 30% of California's urban and agricultural uses. In dry years, groundwater use increases to about 40% of statewide water use and 60% or more in some regions. In some areas, where urban and agricultural water demands exceed available surface water supplies, groundwater overdraft is occurring. Groundwater overdraft is the condition in which the amount of water withdrawn by pumping over the long term exceeds the amount of recharge, and is characterized by groundwater levels that decline over a period of years and never fully recover, even in wet years. Statewide groundwater overdraft is currently 1 to 2 MAF/yr (DWR, 2003). Groundwater overdraft can lead to increased extraction costs, land subsidence, water quality degradation, and environmental impacts such as stream-flow losses and reduced wetland habitat, especially in dry years.

Projected climate change is also expected to impact both surface water and groundwater supplies. Average air temperatures throughout California have increased steadily during the past century. Precipitation rates have remained steady, but April snowpack volumes in the northern Sierra Nevada decreased about 15% between 1950 and 2009, and may decline by as much as 20 to 50% by 2050 (DWR, 2008). The percentage of annual Sacramento River runoff that occurs in the spring declined 10% between 1906 and 2006 (California Environmental Protection Agency, 2009), and is expected to continue to decline with reduced snowpack. The dams and canals that make up California's water storage and delivery infrastructure were designed largely around the historical Sierra Nevada snowpack volume and spring snowmelt pattern.

As surface water availability declines, there may be increased reliance on groundwater. However, groundwater resources will not be immune to climate change, and historical patterns of groundwater recharge may change considerably. Warmer, wetter winters would be expected to increase the amount of runoff available for groundwater recharge, but this will occur at a time of year when some basins are full or being recharged at maximum capacity. Warmer air temperatures may result in reduced spring runoff and higher evapotranspiration, reducing the amount of water available for recharge and surface storage. Changes in seasonal rainfall, snowpack and runoff timing may also require changes in operating procedures for existing dams and facilities, and more active development of conjunctive use and aquifer replenishment programs.

Figure 6. Average annual precipitation, 1961-1990.

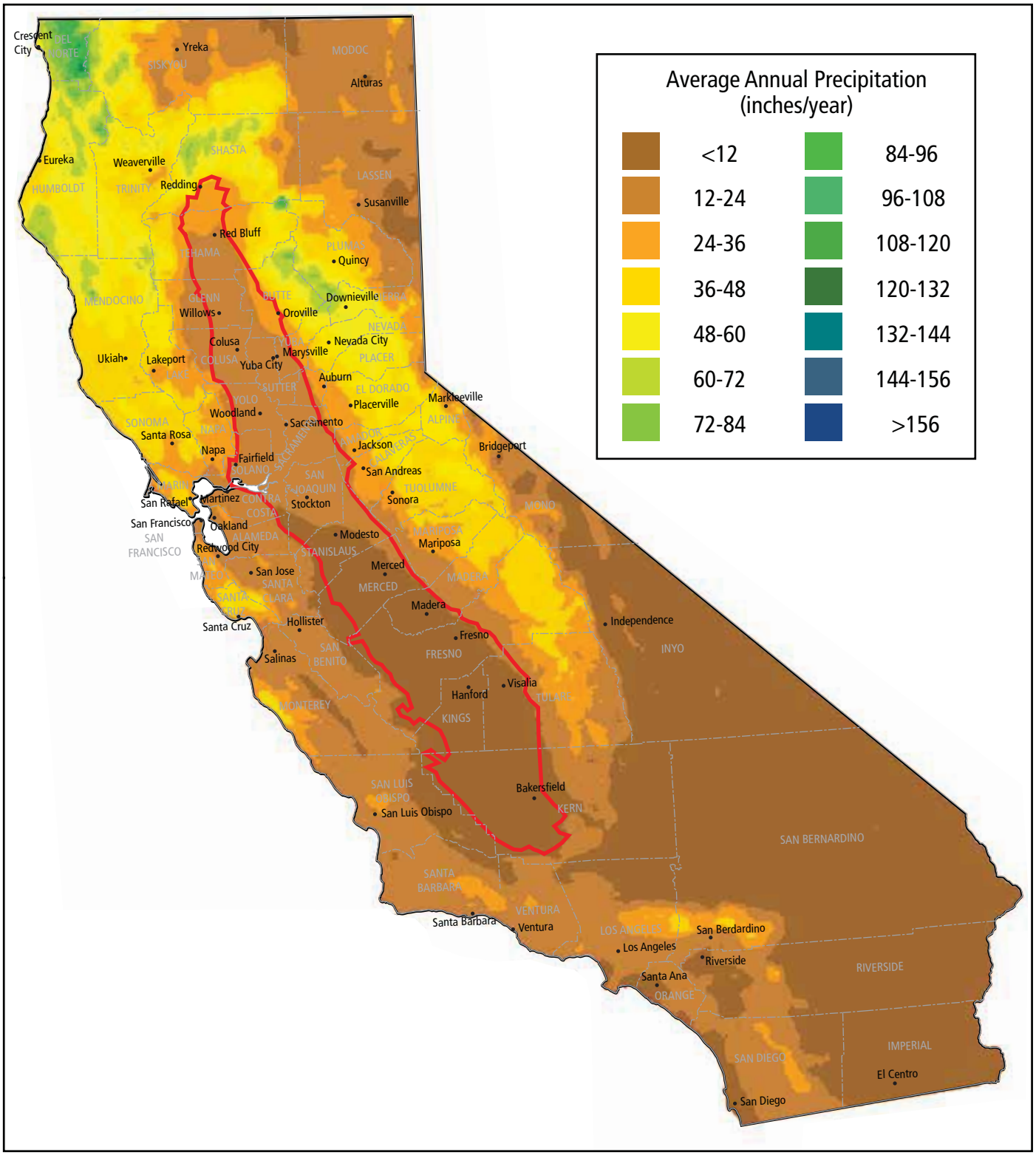
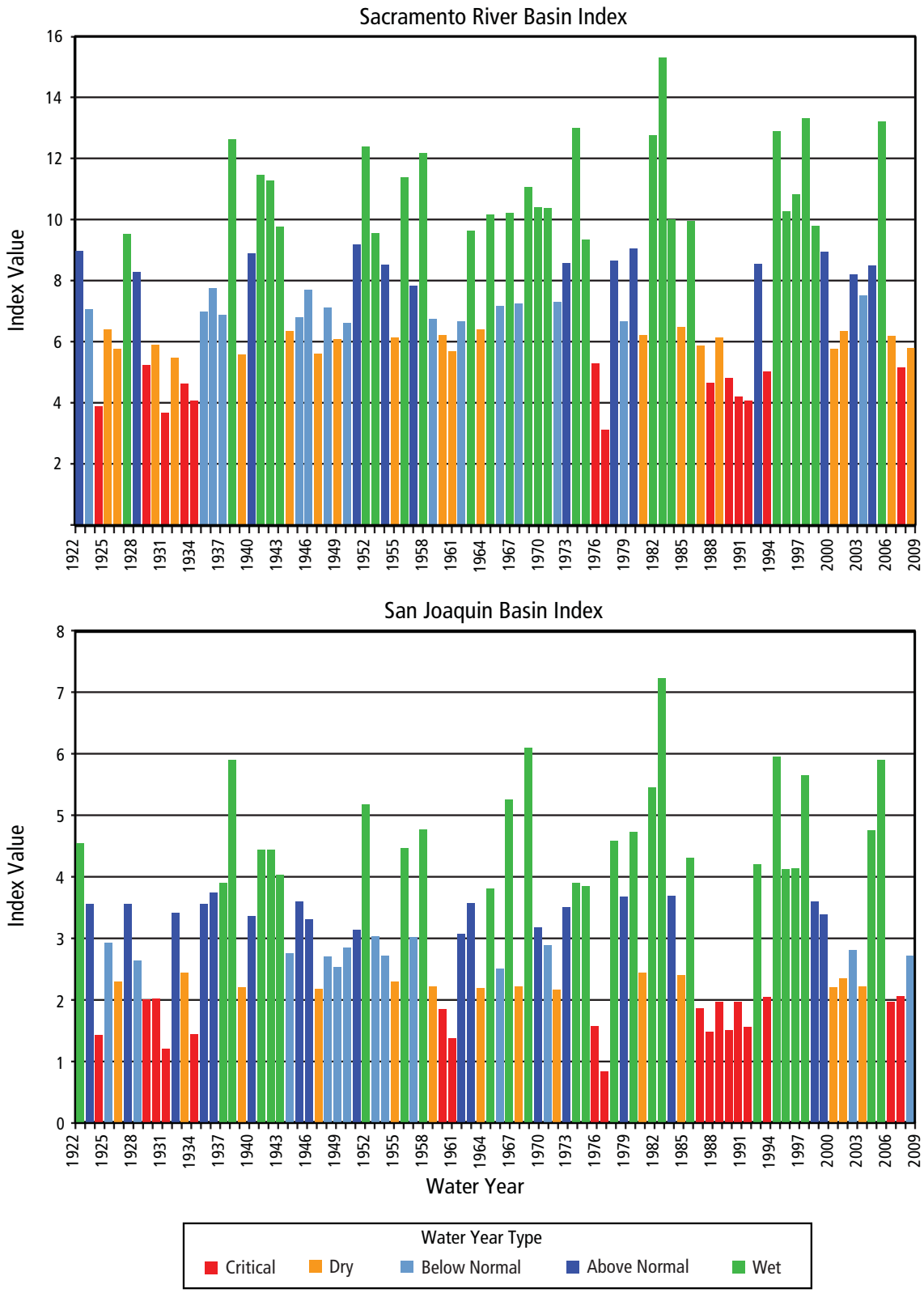


Figure 7. Historical Sacramento River Basin and San Joaquin River Basin Index Values.



Development and Water Use

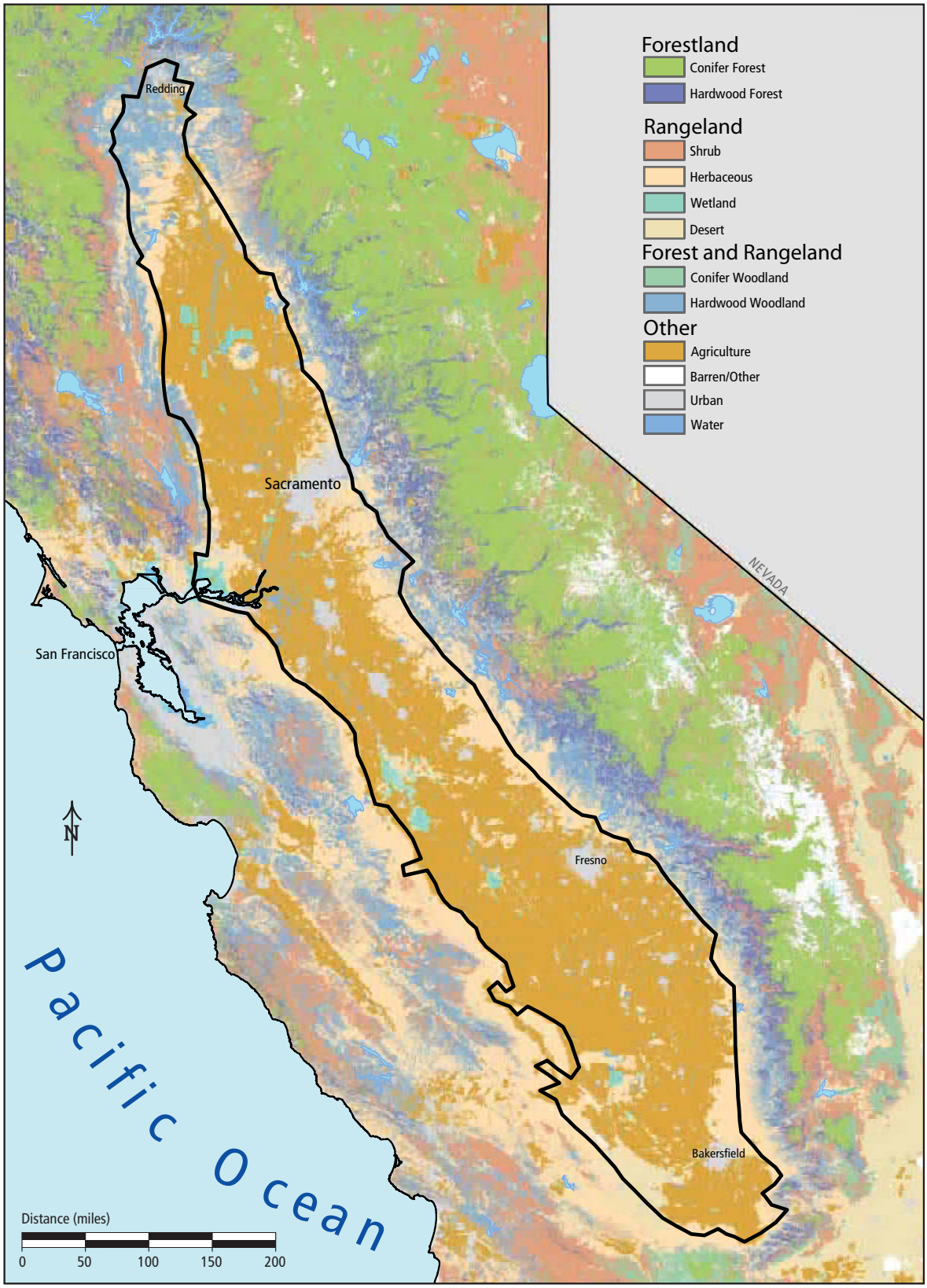
The Central Valley has undergone significant land use changes during the past 150 years. The land area devoted to agriculture expanded from approximately 4,300 mi^2 (11,200 km^2) in 1922 to 10,600 mi^2 (27,400 km^2) in 2009, and the population in the valley increased from less than 732,000 people in 1920 to nearly 8 million people in 2010 (CDOF, 2011). During this period, the area covered by native and riparian vegetation decreased from approximately 15,400 mi^2 (39,800 km^2) in 1922 to 7,500 mi^2 (19,500 km^2) in 2009. Agricultural lands are concentrated along the axis of the Central Valley, with rangelands on the margins and extending into the surrounding mountains, which are dominated by forests (Figure 8). California's Central Valley has experienced steady growth in population and developed land area since the middle of the 19th century (Figure 9).

The expansion of agriculture and urban areas in the Central Valley has been influenced by both the local climate and the availability of water resources, including the development of the surface water supply system. Historically, water development has involved the collection and transport of surface water, the expanded use of groundwater, the conjunctive use of surface water and groundwater and improved water-use efficiency. Surface water development proceeded on three scales: (a) local development, generally capturing water at higher elevations and distributing it at lower elevations within a single watershed, (b) the collection and distribution of water within a hydrologic region, and (c) the transport of water between hydrologic basins (Figure 10).

Population growth is a major factor influencing current and future water use. California's population has increased steadily from 3.4 million in 1920 to more than 37 million in 2010. The California Department of Finance (2012) projects it will reach 60 million by 2050. Between 1920 and 2010, the Central Valley population increased from approximately 600 000 to more than 6 million people, and is projected to grow to more than 11 million by 2050. During the past century, the steadily increasing water demands of urban and agricultural consumers were met primarily through development of an extensive surface water collection, storage and conveyance system, groundwater development and more recently by improving water-use efficiency. As the population continues to grow, many communities are expected to reach the limits of their water supplies. This will result in significant local and regional water-supply challenges.

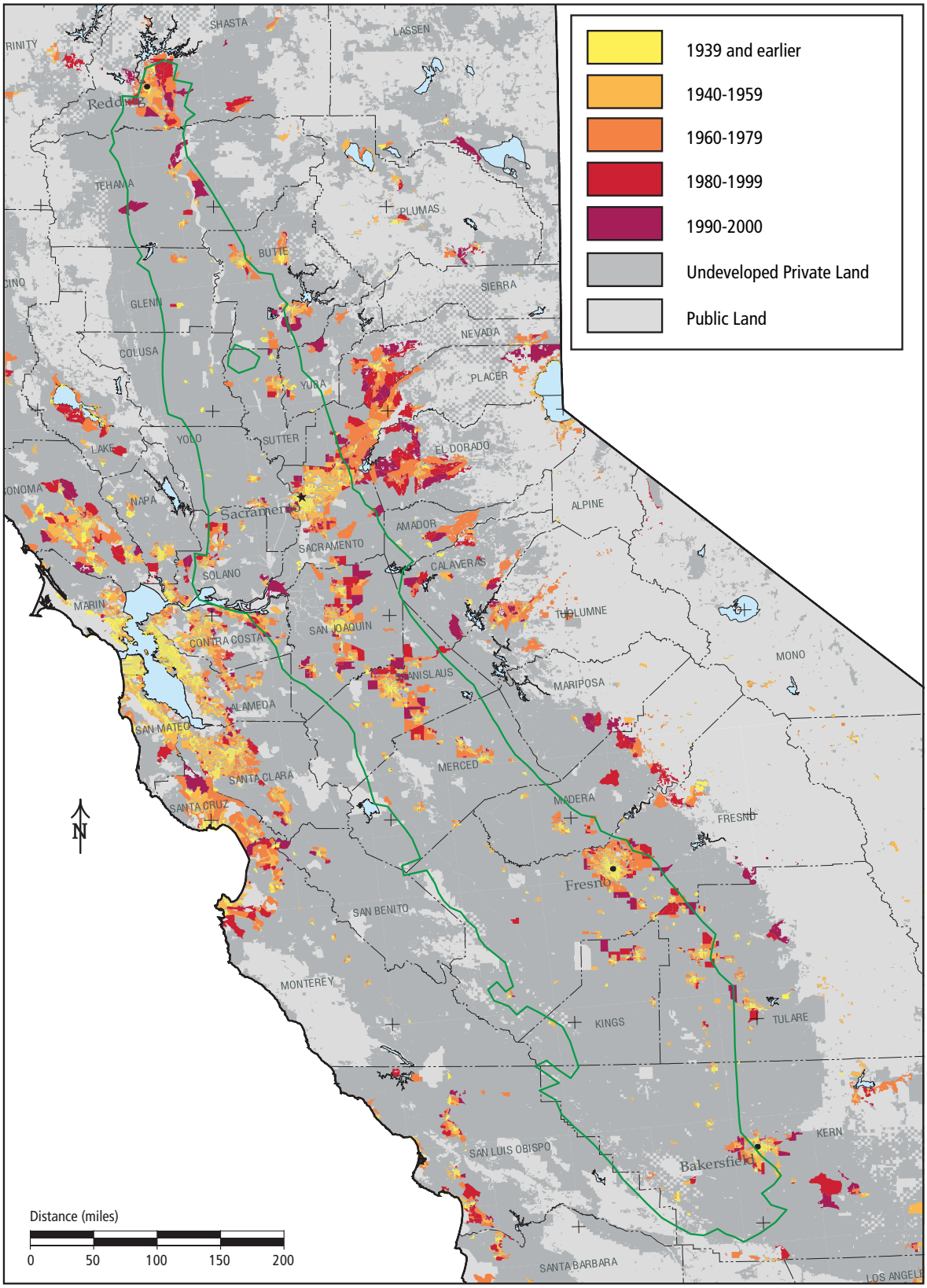
Land-use changes and the construction of surface water storage and delivery systems have resulted in significant hydrologic impacts, including changes in flooding patterns, the balance between runoff and infiltration, seasonal variations in streamflow, and stream-groundwater flows. For example, many naturally intermittent waterways are now perennial streams, with inflows regulated by water storage reservoirs, and channels conveying water supplies, and receiving agricultural drainage and urban wastewater discharges. Many drought-adapted native species have been replaced by exotic species better adapted to more stable flow levels (DWR, 2009).

Figure 8. Vegetation Map.



Vegetation Map from the California Department of Forestry and Fire Protection, 2006.

Figure 9. Urban development in California's Central Valley.



From California Department of Forestry. 2005. Historical Progression of Development.

Figure 10. Major water projects in California.

Reports by Alexander et al. (1873), Grunsky (1898a, 1898b, 1899), Adams et al. (1912), Mendenhall et al. (1916), Harding (1920), California Department of Engineering (1921), Bryan (1923), California Department of Public Works (1927), McGlashan (1929, 1930) and Melcon (1932) summarized the land use, surface water and groundwater resources of the Central Valley before extensive development occurred. The natural groundwater flow pattern prior to development involved groundwater recharge mainly occurring in the upper reaches of stream channels, with groundwater flowing toward discharge zones near the Sacramento River, San Joaquin River or Tulare Lake (Williamson et al., 1989; Bertoldi et al., 1991). Significant artesian flows from confined aquifers were utilized in the early development of agriculture. In the 1920s, the development of the deep-well turbine pump and the increased availability of electricity led to a tremendous expansion of agriculture, which used those high-volume pumps and increased forever the significance of groundwater as a component of water supply in California. Conversion from native vegetation to both dryland and irrigated agricultural land uses resulted in significant increases in recharge to the water table, and a change in the groundwater flow direction in the unsaturated zone from upward (discharge) to downward (recharge) (Scanlon et al., 2005; Williamson et al., 1989).

Human activity has significantly altered the natural surface water and groundwater flow patterns. California has lost more than 90% of the wetlands and riparian forests that existed in 1850, much of this in the Central Valley (DWR, 2009). Construction of reservoirs in the mountains adjacent to the Central Valley to store and regulate the flow of snowmelt to agricultural and urban users has greatly altered the surface water flow regime. Many naturally intermittent channels are now perennial streams conveying irrigation water and collecting agricultural drainage and treated urban wastewater. Land use conversion, groundwater pumping and surface water development have resulted in higher water tables in areas of high irrigation water application, cones of depression centered on areas of high groundwater pumping, and reduced groundwater discharge to rivers.

Groundwater heads have declined throughout much of the Central Valley, with areas in the western and southern parts of the San Joaquin Valley and an area north of the Sacramento-San Joaquin Delta experiencing the largest declines. Excessive groundwater pumping has also caused subsidence of more than 1 ft (0.3 m) between 1900 and 1980 over an area of 5,200 mi^2 (13,500 km^2) in the San Joaquin Valley, mostly in the Tulare Basin and on the west side of the San Joaquin Basin, with a maximum of 30 ft (9 m) near Los Banos (Poland et al., 1975; Ireland, 1986). Excessive groundwater pumping has also caused significant subsidence in Colusa and Yolo Counties in the Sacramento Valley, with a maximum of 3.5 ft (1 m) near Zamora (Blodgett et al., 1990; Lofgren and Ireland, 1973). Surface water imports to these areas have slowed or eliminated subsidence in some areas. Some subsidence has continued to occur owing to groundwater pumping (Brandt et al., 2005), but no comprehensive regional study has documented subsidence after 1990.

Model Development and Calibration

The C2VSim model simulates water movement through the land surface, surface water and groundwater flow systems of California's Central Valley. Model components represent geologic and hydrologic features using a relatively coarse grid. An extensive database of historical data was developed that describes water inflows, diversions, land use and crop acreages from 1922 through 2009. The C2VSim model contains many parameters, some of which were estimated and some of which were calibrated to obtain the best match to historical head, flow and subsidence observations. The calibrated model performs well, with an acceptable match to these observations.

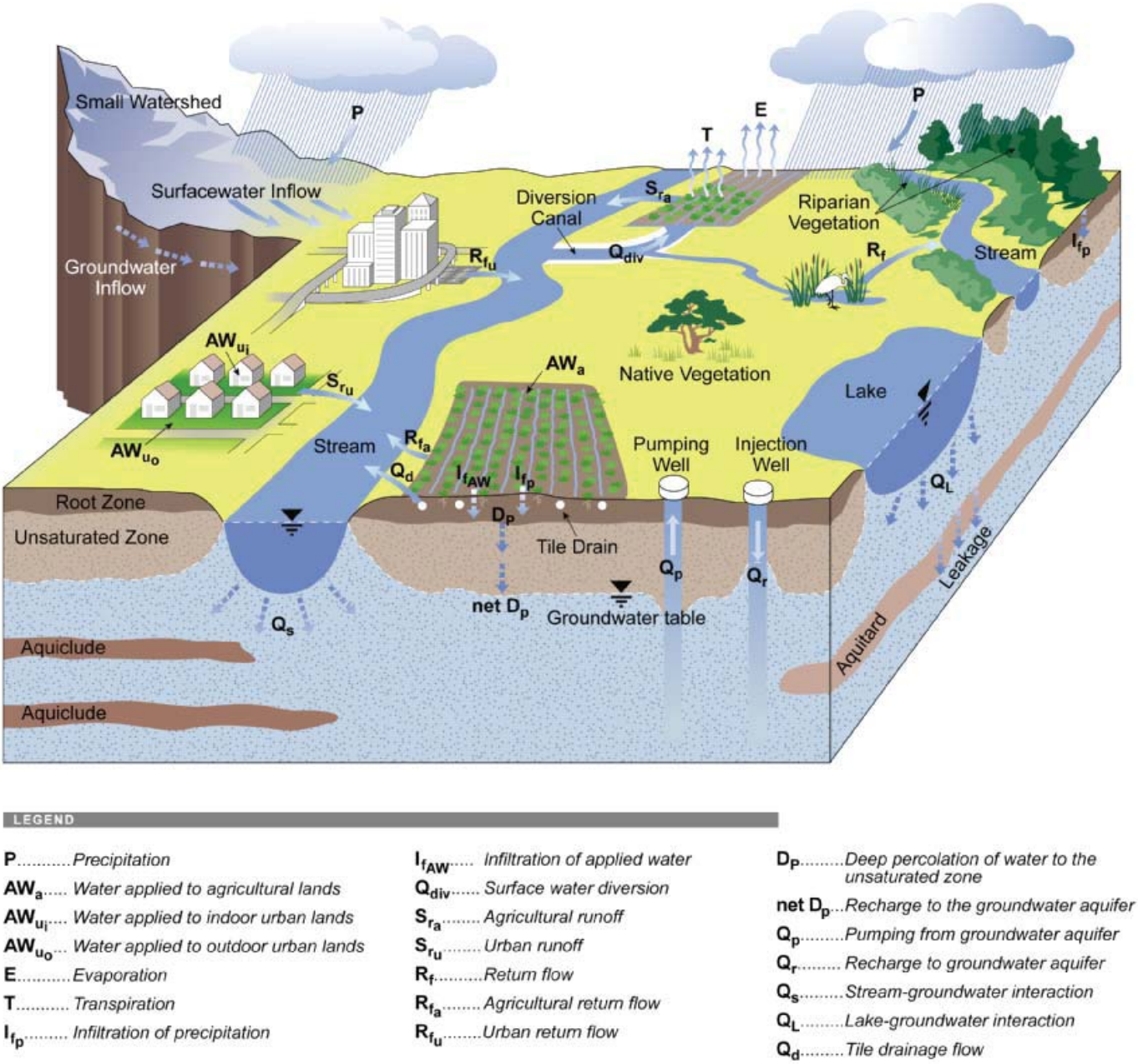
Model Framework

The C2VSim model is run with the Integrated Water Flow Model (IWFM) application, which simulates water movement through the land surface, root zone, unsaturated and saturated parts of the aquifer, lakes and rivers. C2VSim runs on a monthly time step from October 1, 1921 through September 30, 2009. The basic C2VSim model, described in this report, incorporates a finite element grid with 1,392 elements, grouped into 21 water budget subregions. Hydrologic parameters were calibrated to match observed groundwater heads, groundwater head differences between well pairs, surface water flows, and stream-groundwater flows for the period between September 1975 and October 2003, and land surface subsidence observations for the period between September 1957 and September 2004. A detailed description of each model input file is provided in the companion *Users Manual* (Brush and Dogrul, 2012).

Integrated Water Flow Model (IWFM)

The C2VSim model uses version 3.02 of the Integrated Water Flow Model (IWFM) (Dogrul, 2012A, 2012B and 2012C). IWFM is a data-driven, comprehensive hydrologic simulation model 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 ungauged watersheds adjacent to the model boundary (Figure 11). IWFM also simulates water demands based on land-use, soil and climatic properties, and agricultural management parameters as well as water supplies in terms of surface water diversions and groundwater pumping to meet these demands. These features make IWFM an appropriate tool both to simulate historical conditions in a basin and to perform water resources management planning studies for the future. The C2VSim model uses a fairly coarse finite element grid, and attempts to strike an appropriate balance between model accuracy and complexity. The 21 water budget subregions were originally delineated to correspond to the approximate spatial scale at which data was developed for previous DWR studies. The grid and subregion scales are adequate for calculating regional water budgets and their effects on the groundwater and surface

Figure 11. Integrated Water Flow Model components.



water flow systems, owing to the relatively deep water tables and little topographic relief throughout much of the Central Valley (Kendy et al., 2003).

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 demands and water flows through the land surface, 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 user-specified groundwater 'zones'. Text files of groundwater heads and subsidence at each node produced by the Simulation application can be used by the Tecplot™ (Tecplot, Inc. 2011) program to produce movies of changes in aquifer heads and subsidence through time. The IWFM GIS/GUI tool can create ArcMap™ 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/.

CVGSM Model

The C2VSim model is based on the model framework and input data sets of the Central Valley Groundwater-Surface Water Model (CVGSM), which incorporated information from several earlier models. Williamson et al. (1985) published a draft version of the Central Valley Regional Aquifer System Analysis (CV-RASA) groundwater flow model, using the finite difference application developed by Trescot, Pinder, Larson and Torak (Trescott, 1975; Trescott and Larson, 1976; Trescott et al., 1976; Torak, 1982). Boyle Engineering used the model of Williamson et al. (1985) as the basis for a finite element model called the Central Valley Groundwater Simulation Model which incorporated both the surface water and groundwater flow systems (Boyle Engineering Company, 1987). The model of Boyle Engineering (1987) served as the basis for the CVGSM model, developed by James M. Montgomery Consulting Engineers and Boyle Engineering using the finite element Integrated Groundwater and Surface Water Model (IGSM) (James M. Montgomery Consulting Engineers, 1990A and 1990B). Development of the CVGSM model was funded by DWR, USBR, SWRCB, and CCWD.

The original CVGSM project had numerous goals, most notably development of a comprehensive hydrologic database for the Central Valley for the 59-year period from October 1921 to September 1980; development of a model grid that would support regional, sub-regional and site-specific analyses; incorporating variable land uses and crops through time; and estimating rates and distribution of groundwater pumpage (James M. Montgomery Consulting Engineers, 1990B). At the time, the CVGSM input data set was considered to be perhaps the most comprehensive set of water-resources data ever compiled for the Central Valley. The CVGSM model was extended and updated several times. The original model contained data sets to operate on a monthly time step from October 1921 to September 1980. The model was subsequently updated for October 1981 through September 1993 by CH2M Hill (CH2M Hill, 1996), and then from October 1993 through September 1998 by DWR staff.

C2VSim Model Development

In 2001, DWR began a lengthy review of the IGSM numerical engine and the CVGSM model. A peer review of IGSM, conducted by the California Water and Environmental Forum (CWEMF) with assistance from researchers at the University of California at Davis (LaBolle et al., 2002) identified several issues regarding the theory and foundations of IGSM. These included improper implementation of head-dependent boundaries, lack of a methodology to simultaneously simulate coupled processes (such as Surface Water and groundwater flow processes), non-standard formulation of boundary conditions and head-dependent transmissivity, incorrectly reported water budgets, lack of a methodology to assure convergence to non-linear boundary conditions, and inadequate documentation of some portions of the computer code (LaBolle et al., 2002). DWR responded by thoroughly reviewing the existing IGSM code and documentation, refining the theoretical foundation, rewriting significant portions of the code, and producing complete documentation and examples. The updated finite element groundwater-surface water application was named the Integrated Water Flow Model (IWFM). DWR has continued the development of the IWFM application, which is currently at version 4.0 (Dogrul, 2012E and 2012F). The C2VSim model was developed using IWFM version 3.02 (Dogrul, 2012A, 2012B and 2012C).

CVGSM data sets were modified to conform to the IWFM application format, and were updated to simulate the period from October 1921 through September 2009, and the resulting model was named the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim). The updated model incorporates numerous improvements and expanded data sets, notably spatiotemporally distributed precipitation, removal of constant-head nodes in the Sacramento-San Joaquin Delta, re-configured hydrology for the rivers and lakes in the Sacramento-San Joaquin Delta and Tulare Basin, significant expansion of the surface water diversions database, updated initial aquifer heads in October 1921 and October 1972, detailed delineation of intermittent mountain-front watersheds, refined vertical discretization of aquifer layers, re-configured tile drains, and the separation of agricultural and urban surface water diversions and groundwater pumping. The resulting model was calibrated to obtain the best match to observed groundwater heads and surface water flows for the period October 1975 through September 2003. Subsidence observations were not available for the calibration period, so subsidence parameters were calibrated separately to match subsidence observations for 1926-1970 in the San Joaquin and Tulare basins from Poland et al. (1975) and for the period 1942-1964 in the Sacramento Valley from Lofgren and Ireland (1973).

C2VSim Model Grid

The C2VSim model is based around the two-dimensional finite element grid developed for the CVGSM model (James M. Montgomery Consulting Engineers, 1990A and 1990B). The C2VSim model uses the nodes and elements of the CVGSM finite element grid, and the grouping of grid elements into model subregions (Figure 12). The C2VSim model incorporates significant modifications related to aquifer stratigraphy and the locations of lakes, river segments and river reaches. The following description of the two-dimensional finite element grid is derived from the CVGSM model documentation of James M. Montgomery Consulting Engineers (1990A and 1990B).

Nodes and Elements

The finite element grid is based on 1,393 nodes located in the alluvial portion of California's Central Valley. The individual nodes are delineated in an X-Y coordinate system with the origin arbitrarily taken as the intersection of the line of lat 35° N and the 750 000 line of UTM zone 10N (between long 120° and 121° W). These nodes are combined into 1,392 triangular and quadrilateral elements. Grid characteristics are listed in Table 2.

Table 2. C2VSim model grid characteristics

Nodes	1,393
Triangular elements	263
Quadrilateral elements	1,129
Total elements	1,392
Layers	3

The following criteria were used to delineate the nodes and elements of the CVGSM model grid (James M. Montgomery Consulting Engineers, 1990A and 1990B):

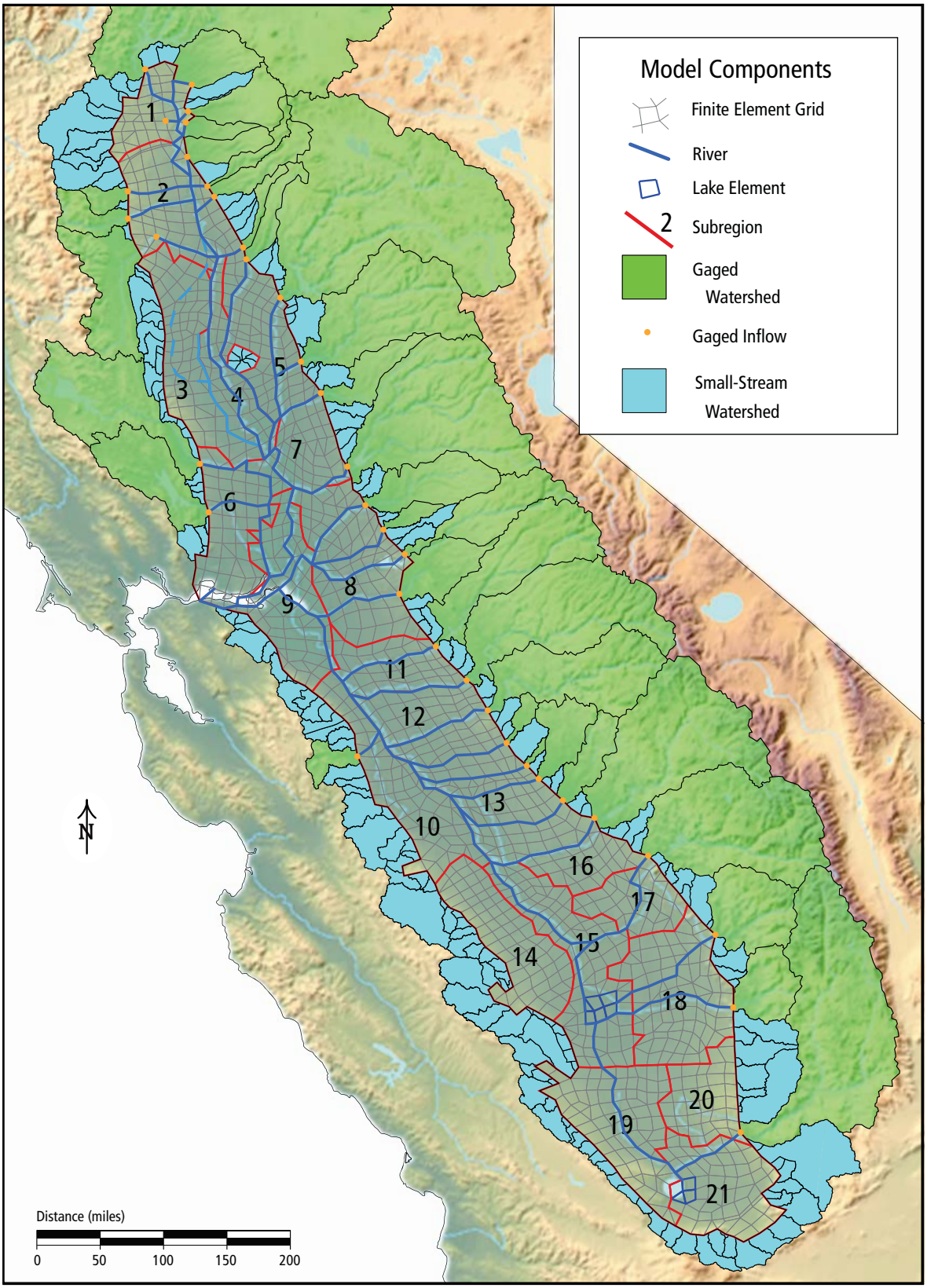
- The model boundary conforms to the geologic boundary of the Central Valley;
- Grid lines follow the major streams and creeks, are parallel to stream-flow direction, and incorporate the surface drainage patterns;
- Grid orientation generally follows expected groundwater streamlines;
- Element meshes are relatively finer in the vicinity of observed steep groundwater gradients;
- Thin strips of elements are delineated parallel to faults that act as barriers to horizontal groundwater flow; and
- Element boundary lines match the predefined boundary lines of 21 model subregions.

Rivers

Surface water flow is simulated using lakes and rivers. Rivers are constructed from river segments, one-dimensional line elements with the ends located at grid nodes. River reaches are constructed from river segments, and linked into a contiguous network in which two or more upstream reaches end at a specific grid node, and one downstream reach begins at the same grid node. Vertical water flow between each river node and the co-located groundwater node is a function of the groundwater head, the river stage, and the hydraulic conductance of the riverbed.

The CVGSM model used 431 river nodes to simulate 72 reaches. The CVGSM

Figure 12. C2VSim coarse-grid model framework.



river network was modified for the C2VSim model, resulting in a river network that uses 449 river nodes to simulate 75 reaches. The locations of the stream nodes inherited from the CVGSM model were retained, but their properties underwent several modifications. The river reach representing the Glenn-Colusa Canal was disabled by eliminating flows into the reach, reallocating surface element drainage to other reaches, and setting the riverbed conductances to zero. Constant head boundary conditions at 30 groundwater nodes in the Sacramento-San Joaquin Delta area in the CVGSM model were eliminated, converting these to simulated heads. River bottom altitudes were adjusted as necessary so they were always beneath the ground surface altitude at the corresponding node. In addition, three river reaches were added. A river reach was delineated following the Kern River Flood Channel from Buena Vista Lake to Tulare Lake, simulating the surface water flow outlet from the southern Tulare Basin. River reaches were also added to simulate the Suisun Marsh and to extend the Sacramento-San Joaquin river channel to the Carquinez Strait.

Lakes

Each simulated lake covers the entire area of one or more model elements. Two lakes were simulated in the CVGSM model grid. Buena Vista Lake was formed by four model elements, receiving all discharge from the Kern River, and having no flow outlet. Tulare Lake was formed from six model elements, receiving all discharge from the Kaweah, Tule and South Fork Kings rivers, and discharging to the North Fork Kings River downstream from the Army Weir.

Buena Vista Lake was operated as a reservoir until the construction of Lake Isabella. Since the early 1940s, the area delineated as Buena Vista Lake is largely farmed, with three small inundated areas. Tulare Lake was once one of the largest inland water bodies in the United States, with an estimated surface area of 790 mi^2 in 1868, but diversion of inflows to agriculture caused the lake to dry up completely by 1899 (ECORP Consulting Inc., 2007). Little surface water has reached the lake bed since the late 1890s, and the lake bed is currently farmed. The construction of the Army Weir and Crescent Weir on the Kings River, and the construction of storage reservoirs on the Kaweah and Tule rivers have significantly reduced flood flows to Tulare Lake.

The areas delineated as Buena Vista and Tulare lakes in the CVGSM model did not conform to the areas of these lakes. For the C2VSim model, each lake retained the same number of elements, but the elements were changed. The CVGSM model also did not provide a flow outlet for Buena Vista Lake; the Kern River Flood Channel was added to the C2VSim model to provide continuity to the surface water flow representation and to carry discharges from the Kern River and Buena Vista Lake.

The two lakes delineated in the C2VSim model do not accurately represent the actual states of the hydrologic system in their respective areas. Owing to a limitation in the version of the IWFM application used for the C2VSim model, each model element is either a land surface element simulated with the Land Surface Process, or a lake element simulated with the Surface Water Flow Process. The extensive data sets developed for the CVGSM model, which served as the foundation for the C2VSim model, do not include land use data for these elements. To date no land use information has been developed for these elements. A new version of the IWFM application, currently under development, will allow simulation of intermittent flooding of the Buena Vista and Tulare lake beds (Dogrul, 2012F).

Subregions

Model elements are grouped into subregions comprised of contiguous grid elements to facilitate data entry and reporting of model results. The C2VSim model uses the 21 subregions developed for the CVGSM model (Figure 3 and Table 1). These subregions were based on Depletion Study Areas (DSAs) developed by DWR's Division of Planning. For the Redding Basin, one subregion was delineated as the portion of DSA 58 that lies within the geologic boundary of the Central Valley. In the Sacramento River Basin, model subregions generally conform to DSAs. Land within the model area that did not fall within a DSA was incorporated into DSA 65. DSA 55 corresponds roughly to the administrative boundary of the Sacramento-San Joaquin Delta. South of the Sacramento-San Joaquin Delta, the entire Central Valley falls into DSA 49 (San Joaquin Basin) and DSA 60 (Tulare Basin). These DSAs were divided into 4 and 8 subregions, respectively, along hydrologic and administrative boundaries. These subregions were named DSA 49A to 49D and DSA 60A to 60H.

Aquifer Layers

The groundwater flow system is simulated with a three-layer finite-element groundwater model. The top of the groundwater flow system is defined as the land surface, and the bottom is defined as either the relatively impermeable basement rocks, or, where present, the base of fresh water. Three layers were considered sufficient to represent the vertical distribution of groundwater pumping while maintaining relatively fast run times (CH_2M Hill, Inc., and S.S. Papadopoulos and Associates, 2006). The thicknesses of the three layers and the Corcoran Clay confining unit between the top and middle layers are shown in Figure 13. In general, the top layer was delineated to represent the unconfined portion of the aquifer, the middle layer to represent the portion of confined aquifer in which groundwater

Figure 13A. Thickness of the top model layer.

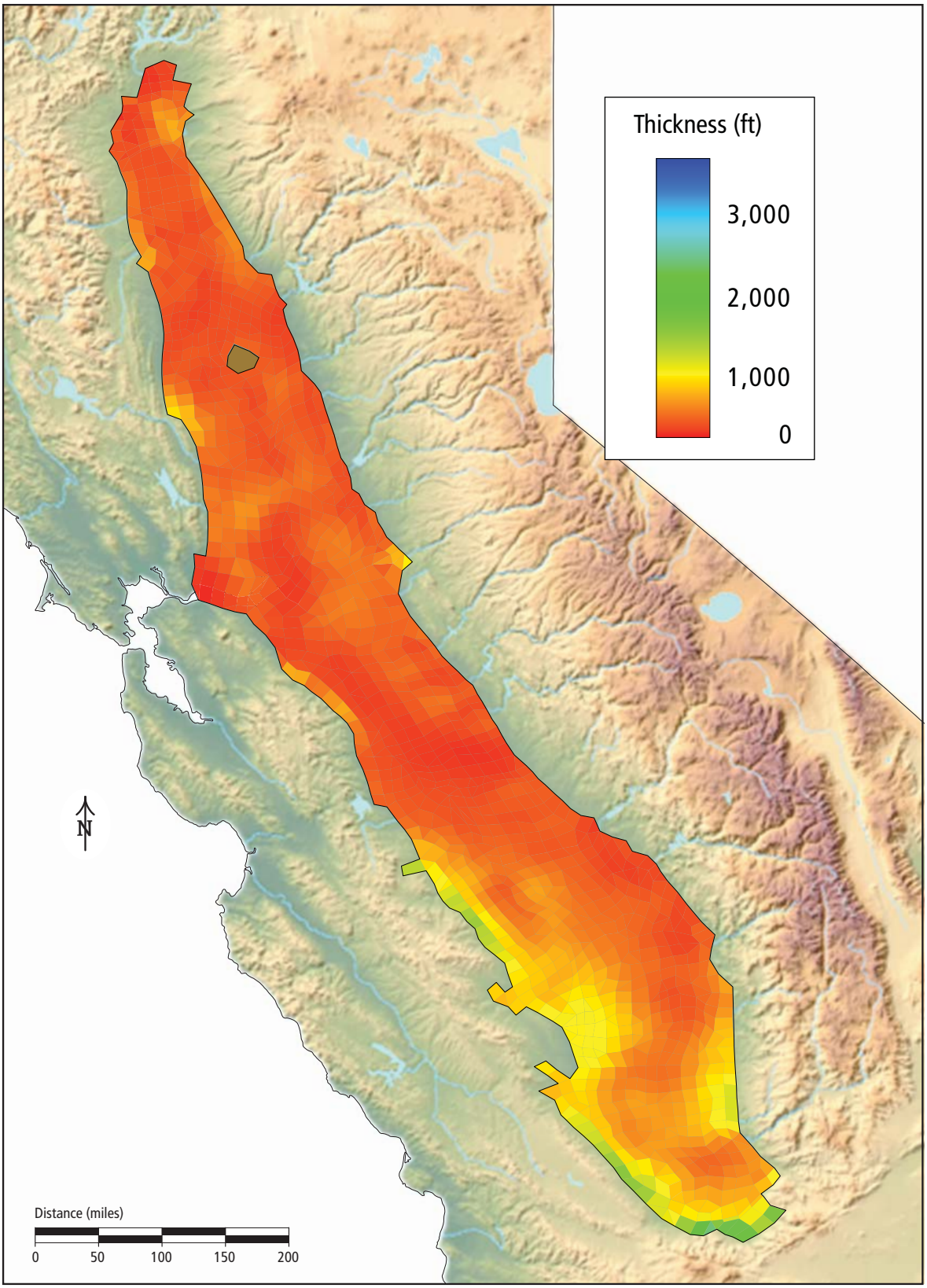


Figure 13B. Thickness of the Corcoran Clay.

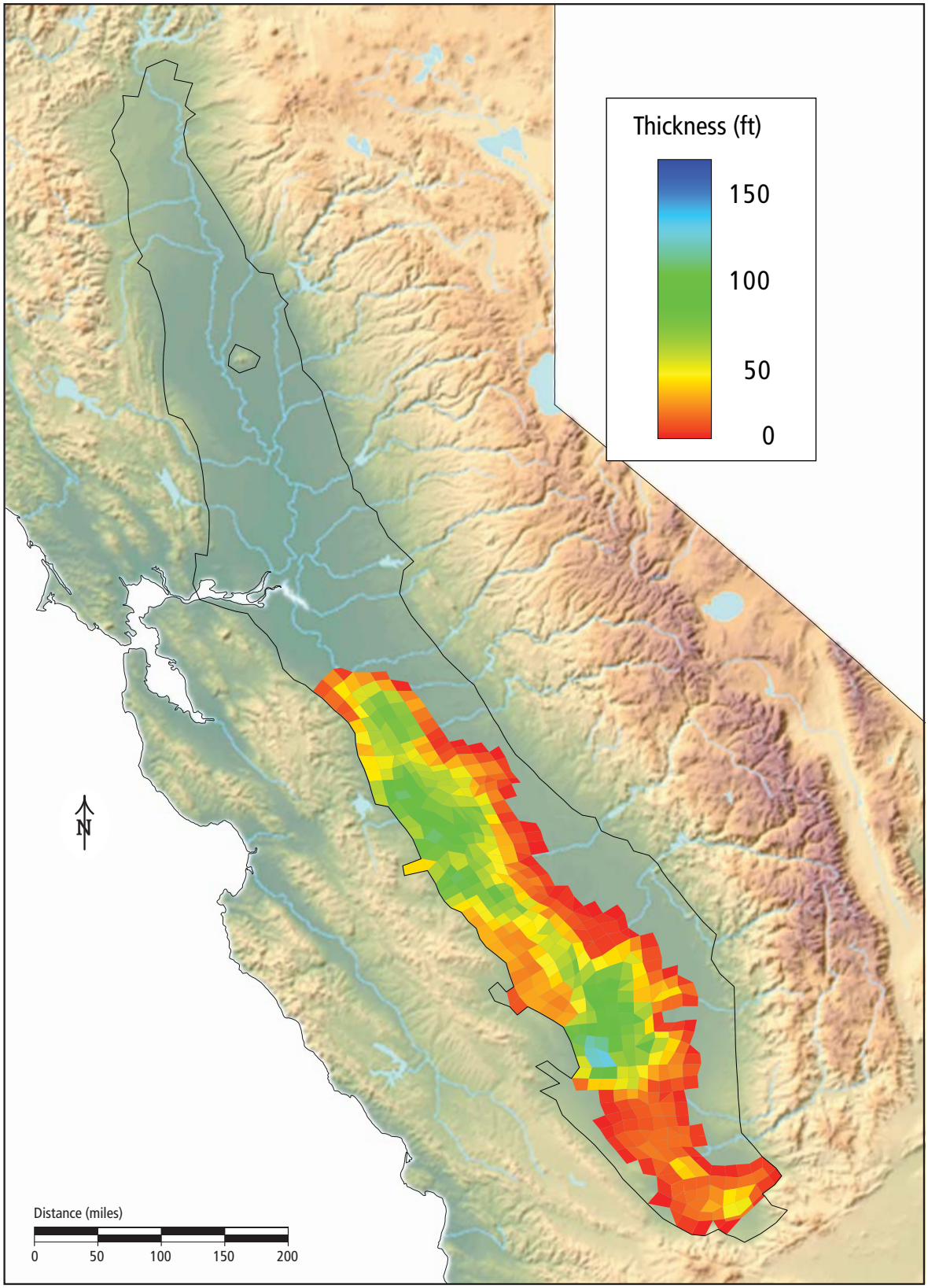


Figure 13C. Thickness of the middle model layer.

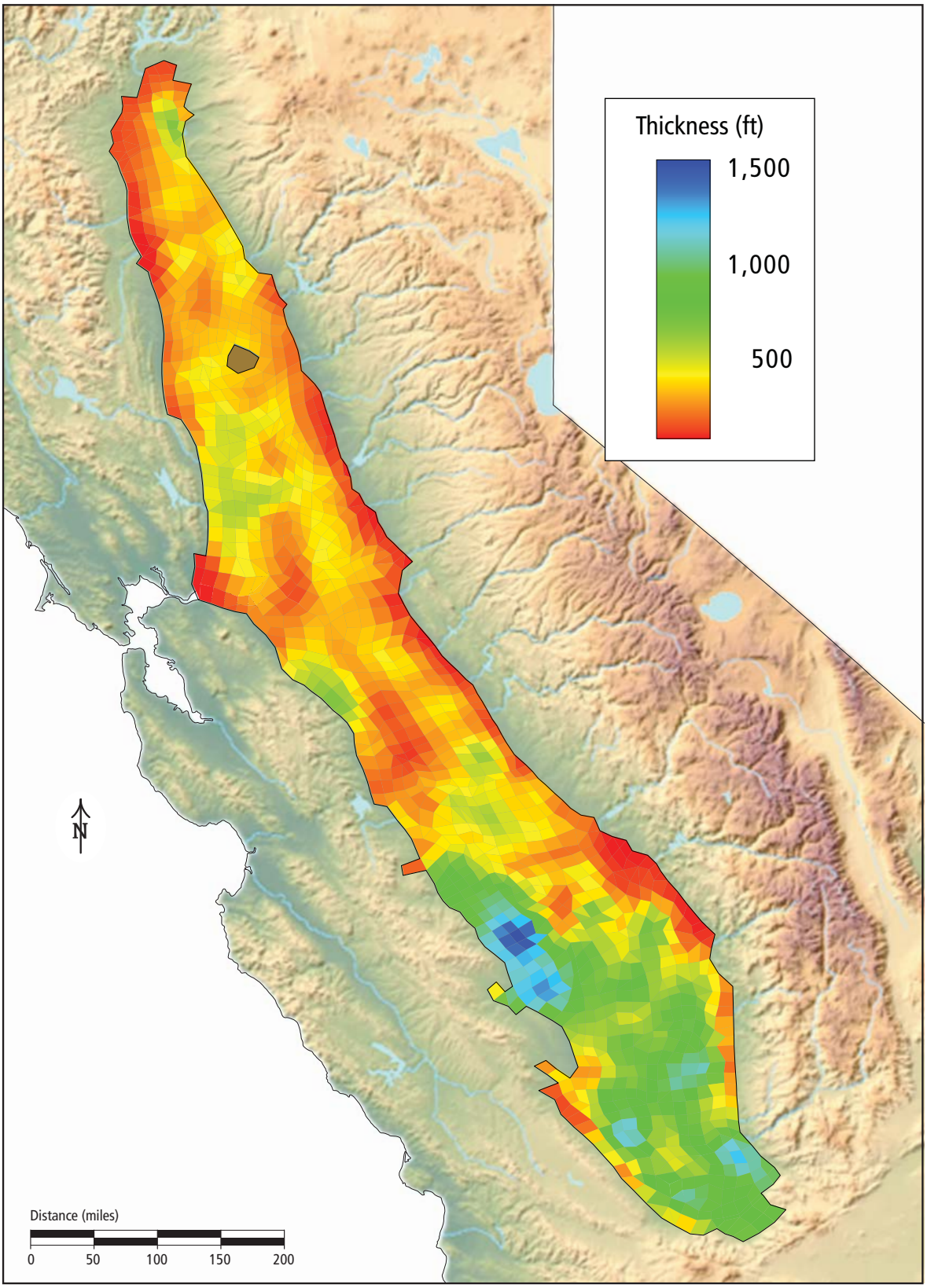
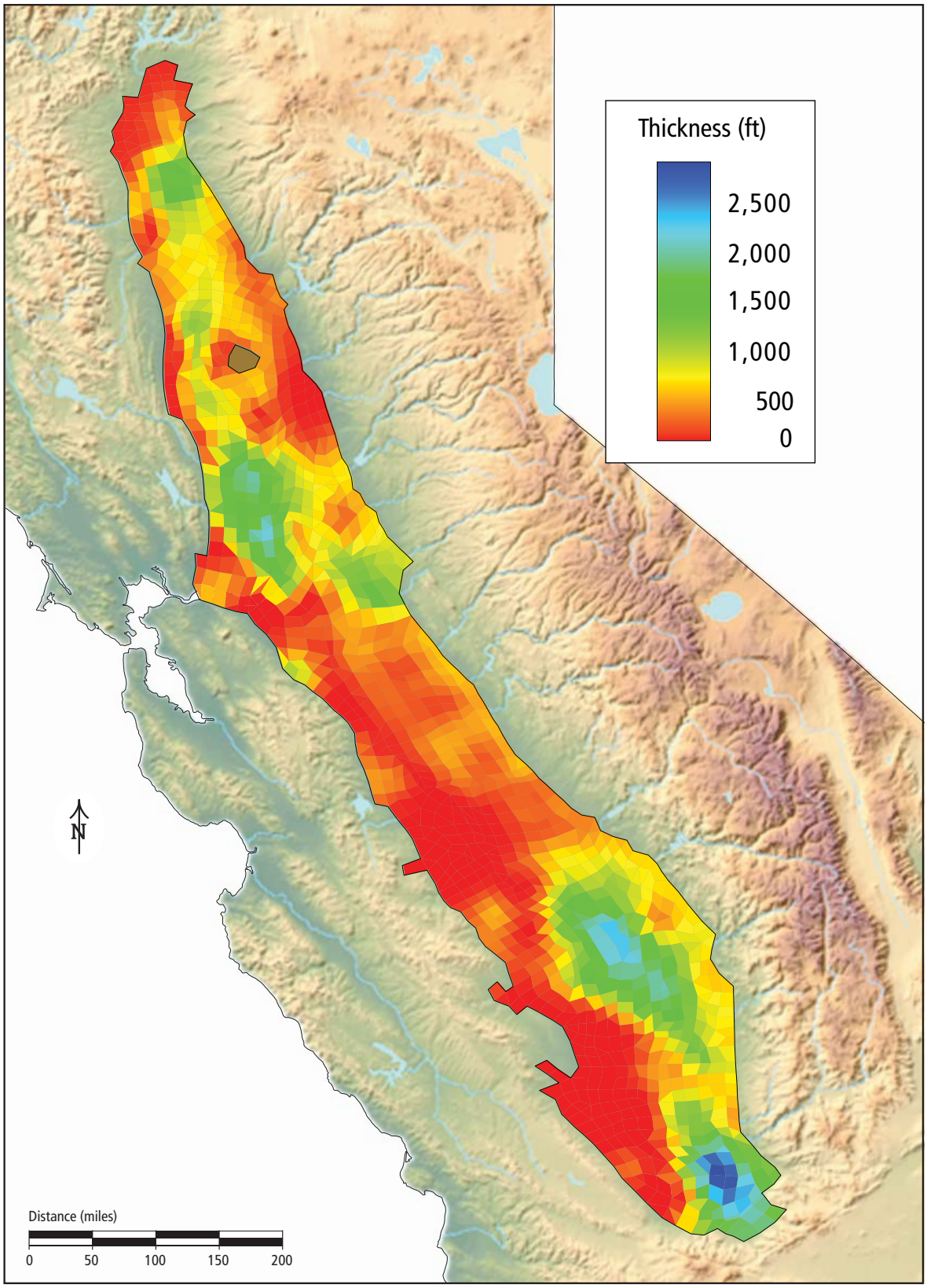


Figure 13D. Thickness of the bottom model layer.



pumping occurs, and the bottom layer to represent the portion of the confined aquifer where no pumping occurs. Where the Corcoran Clay is present, it defines the vertical boundary between the top and middle aquifer layers.

The total aquifer thickness of the C2VSim model was derived from the groundwater flow model developed for the USGS's Central Valley Regional Aquifer System Analysis (CV-RASA) program (Williamson et al., 1989). The Redding Basin was not included in the CV-RASA model, so the total aquifer thickness for this area was taken from the Redding Basin Water Resources Management Plan (CH_2M Hill, Inc., 2001), and was divided into three layers of equal thickness.

The ground surface altitude for the C2VSim model was derived from the USGS National Elevation Dataset. The land surface altitude varies between a maximum of 3,451 ft and a minimum of -10 ft. The base of the top model layer of the CV-RASA model of Williamson et al. (1989) was used as the bottom of the top model layer of the C2VSim model, with several modifications outside the Redding Basin to reduce layer drying. Two maps of low groundwater levels were developed, one based on 1976 water levels, and the other based on the lowest recorded water level from the DWR Water Level Library database. In areas where the lowest water level elevation from the two maps was less than 100 ft above the base of the layer, the layer bottom was lowered to provide a minimum saturated thickness of 100 ft (CH_2M Hill, Inc., and S.S. Papadopoulos and Associates, 2006). The saturated thickness of the top model layer at the lowest water levels ranges from 100 to 500 ft throughout most of the model area, and as much as 700 ft in the area where the Corcoran Clay is deep. The total thickness of this layer, including the unsaturated zone between the land surface and the water table, and the unconfined portion of the aquifer, is shown in Figure 13A.

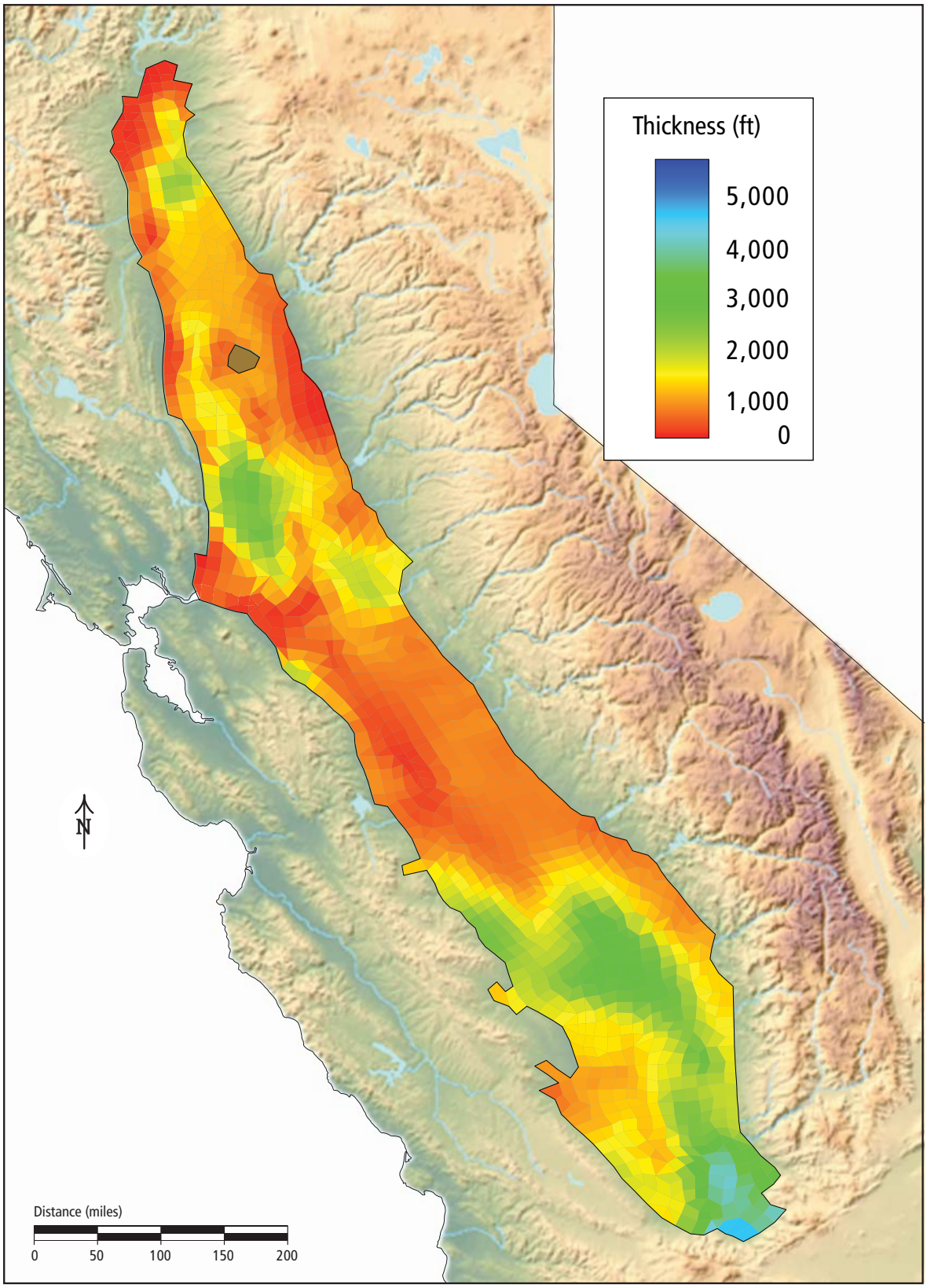
The Corcoran Clay Member of the Tulare Formation is an extensive regional aquitard on the western side of the San Joaquin and Tulare basins. In the C2VSim model, the Corcoran Clay is simulated as an aquitard between the top and middle aquifer layers. The Corcoran Clay top and bottom altitudes of the CV-RASA model of Williamson et al. (1989) were used in the C2VSim model, with several modifications to extend it to the western model boundary (CH_2M Hill, Inc., and S.S. Papadopoulos and Associates, 2006). The maximum thickness of the Corcoran Clay is 180 ft (Figure 13B).

The base of the middle model layer of the CV-RASA model of Williamson et al. (1989) was also used as the bottom of the middle model layer of the C2VSim model (outside the Redding Basin). Where the base of the middle layer would be above the base of the top layer, due to the modifications described above, a 10-ft minimum thickness was imposed. The thickness of the middle layer (figure 13C) ranges from 20 to 1,479 ft. In the southernmost portion of the model, some wells appear to be screened below the reported base of fresh water; for this model the layering of the CV-RASA model was retained for consistency, but special attention should be applied to this area in the future (CH_2M Hill, Inc., and S.S. Papadopoulos and Associates, 2006).

The base of the bottom model layer was defined as either the base of fresh water or the basement complex (relatively impermeable igneous and metamorphic rocks

and the Cretaceous Great Valley sequence). Several data sources were used to define this (CH_2M Hill, Inc., and S.S. Papadopoulos and Associates, 2006), listed in order of preference: a map of the base of fresh water for Yuba County developed by Montgomery Watson Harza (2004); the base of fresh water map of the Sacramento Valley of Berkstresser (1973); the base of fresh water map of the San Joaquin Valley of Page (1973); the CV-RASA model of Williamson et al. (1989); and the Redding Basin Water Resources Management Plan (CH_2M Hill, Inc., 2001). In areas where the mapped base of fresh water is above the base of the middle model layer, a 30-ft minimum thickness was imposed on the bottom model layer. The thickness of the bottom layer ranges from 30 to about 3,000 ft (Figure 13D). The total simulated aquifer thickness ranges from 273 to 5,886 ft (Figure 14).

Figure 14. Simulated thickness of the Central Valley aquifer.



Historical Data

The information in the C2VSim input and output files can be used to show where water comes from, where it goes, and how the Central Valley hydrologic system has evolved from the early 1920s. The C2VSim input files detail precipitation, surface water inflows, and surface water exports. The C2VSim model calculates evapotranspiration, Delta outflows, and flows to and from groundwater.

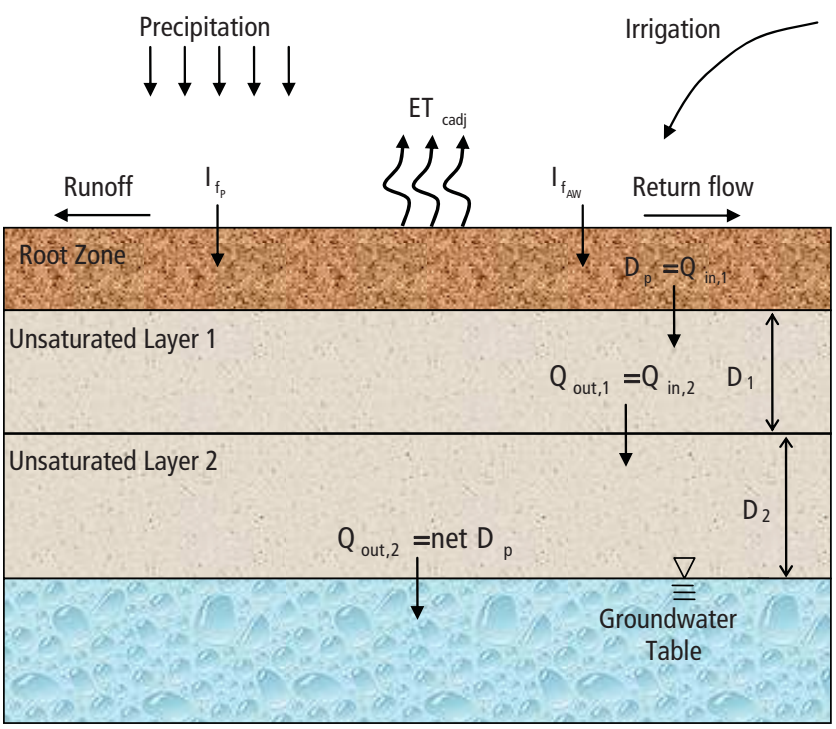
Land Surface Process

The IWFM Land Surface Process simulates water movement over the land surface and through the root zone (Figure 15). The Land Surface Process calculates the water balances for four land use categories: agricultural crops, urban areas, native vegetation and riparian vegetation. A water balance is calculated for each land use class for each of the C2VSim model's 21 subregions for different soil types. The Land Surface Process partitions precipitation to runoff and infiltration, uses land use, soil, climate and crop management information to calculate water demands, allocates available water to meet these demands, and routes excess soil moisture to deep percolation. Sources of precipitation, land use and crop areas and data to calculate water demands are detailed below.

Precipitation

The C2VSim model uses monthly distributed precipitation rates estimated with the Parameter Elevation Regression on Independent Slopes Model (PRISM) by the PRISM Climate Group at Oregon State University. PRISM uses a knowledge-based system that utilizes point-based climatic precipitation and temperature observations to create a digital grid of estimated monthly climatic values over a 2 km square grid (PRISM Climate Group, Oregon State University, http://www.prism.oregonstate.edu/). Precipitation rates from the 2 km x 2 km PRISM grid were aggregated to each C2VSim element and each C2VSim small-stream watershed.

Figure 15. IWFM land surface process.



Evapotranspiration

The C2VSim model includes monthly evaporation rates for each agricultural crop, urban outdoors, native vegetation, and bare soil for each subregion, and for each small-

stream watershed. The model uses a single annual set of monthly evapotranspiration rates, which are repeated for each simulation year. In reality, evapotranspiration rates have changed through time owing to improvements in crop water use efficiency, irrigation efficiency and water distribution systems. However, the precision of the evapotranspiration rates used in the water budget calculations is not expected to be critical (Xu and Chen, 2005). An error analysis determined that the use of evapotranspiration rates that do not change from year to year probably has less impact on simulation results than other error sources such as uncertainties in annual crop acreages and the farm water management practices.

Land Use

The C2VSim model contains a detailed database of historical land use and crop acreages for each model subregion on an annual basis for water years 1922 to 2009. The area of each model element can be allocated among four land use classes. For the C2VSim model, the riparian land use class is only used within the Sacramento-San Joaquin Delta subregion. Land use data and agricultural crop acreages for water years 1922 to 1980 was derived from the CVGSM model (James M. Montgomery Consulting Engineers, 1990A and 1990B). This data was originally derived from DWR hydrology development studies including DWR's Consumptive Use model (DWR, 1979) and Department of Water Resources Simulation Model (DWRSIM; Chung et al., 1989). CH2M Hill (1996) reviewed and modified CVGSM land use and agricultural crop data for water years 1992 to 1980, and compiled data for water years 1981 to 1993. These studies utilized elemental land use distributions for 1954, 1980 and 1993, and interpolated and extrapolated these land uses to other water years (CH2M Hill, 1996). DWR staff compiled land use and agricultural crop data for water years 1999 to 2009 utilizing agricultural commissioners' reports.

Table 3. Agricultural crop categories used in the C2VSim model.

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

Agricultural Water Demand

Agricultural water demand is dynamically calculated for each model subregion each month by the IWFM Land Surface Process. Crops are aggregated to 14 categories in the C2VSim model (Table 3). Crop acreages are supplied for each water year (October 1 through September 30) for water years 1922 to 2009. The crop mix is assumed to remain constant for each water year. The total agricultural water demand for each model subregion is calculated by multiplying the evapotranspiration rate of each crop by the crop acreage, dividing it by the irrigation efficiency, and summing the results. The Land Surface Process then uses stored soil moisture and a combination of surface water diversions and groundwater pumping to satisfy this demand.

Urban Water Demand

Urban water demand is divided into two components, indoor water demand and outdoor water demand. Monthly urban indoor and outdoor water use for water years 1922 to 1993, compiled for the CVGSM model based on DWR's Consumptive Use model (CH_2M Hill, 1996), were utilized in the C2VSim model. These were extended through water year 2009 by DWR staff, based on estimated changes in urban populations.

Native and Riparian Vegetation Water Demand

The total water demand of native and riparian vegetation is calculated for each subregion by multiplying the evapotranspiration rate, by the total acreage of each land use class. The only water source the land use process utilizes to meet this demand is stored soil moisture.

Surface Water Process

The IWFM Surface Water Process calculates a water balance along each river reach between upstream inflows, downstream outflows, diversions, runoff, return flows and stream-groundwater flows (Figure 16). The C2VSim model contains a detailed database of historical monthly river inflow values and surface water diversions, and calculates surface water inflows from small ungauged tributary watersheds at run time. In the model, the Central Valley surface water inflows are divided into three categories: specified river inflows, surface water imports, and calculated tributary inflows (Figure 17). Tributary inflows are dynamically calculated as the outflow from 210 small-stream watersheds (Figure 12).

Inflows

Historical monthly river inflow values were collected for 36 rivers that enter the Central Valley from the surrounding mountains (Figure 17). Several canals also divert water through wasteway canals into river beds for downstream diversion to end users. These deliveries are treated as inflows to downstream river nodes in the C2VSim model. Water is diverted from the Friant-Kern Canal into the Kings River, Kaweah River, Tule River and Kern River. Water is also diverted from the Cross-Valley Canal into the Kern River. Sources for these time series are detailed in the companion report, *Historical Rim Inflows, Surface Water Diversions and Bypass Flows* (Brush, 2012).

Figure 16. IWFM river process.

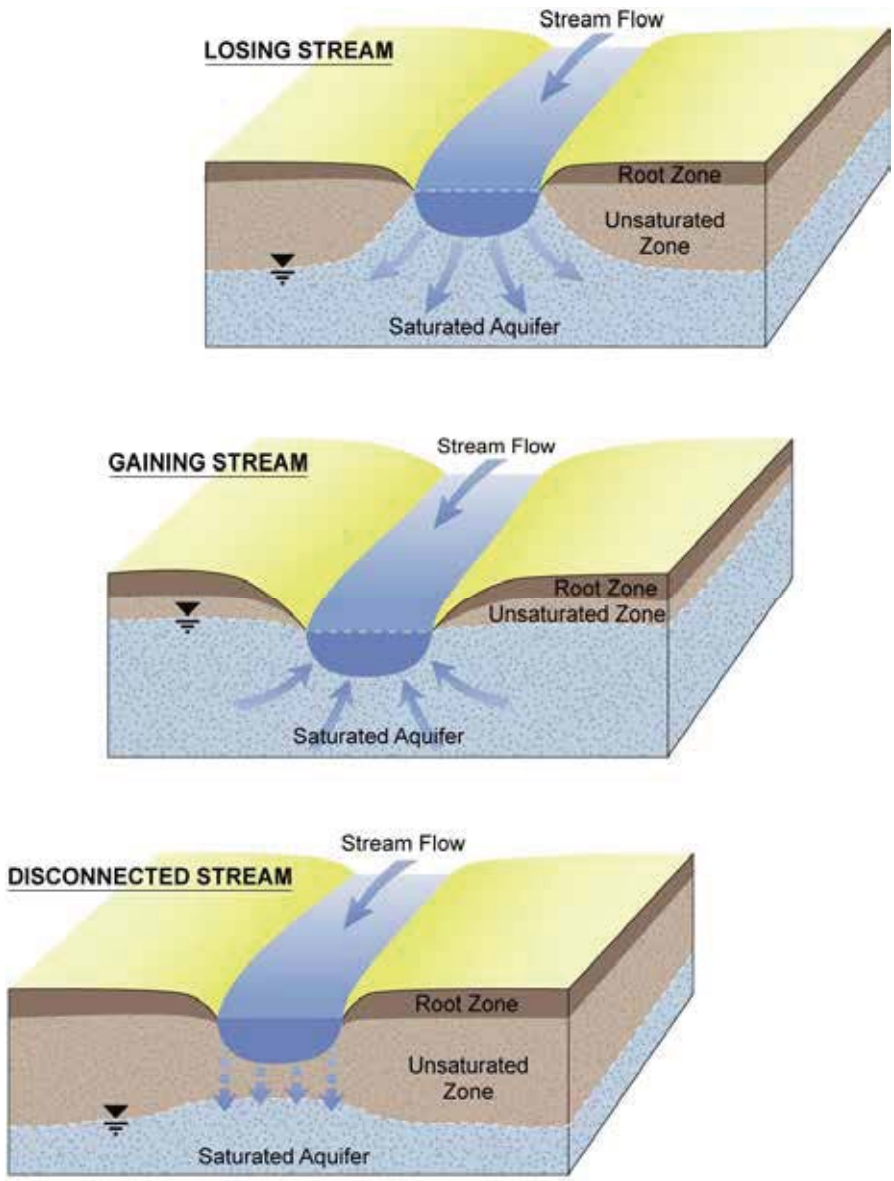


Figure 17A. C2VSim coarse grid with rim inflow, surface water diversion and surface water bypass Locations.

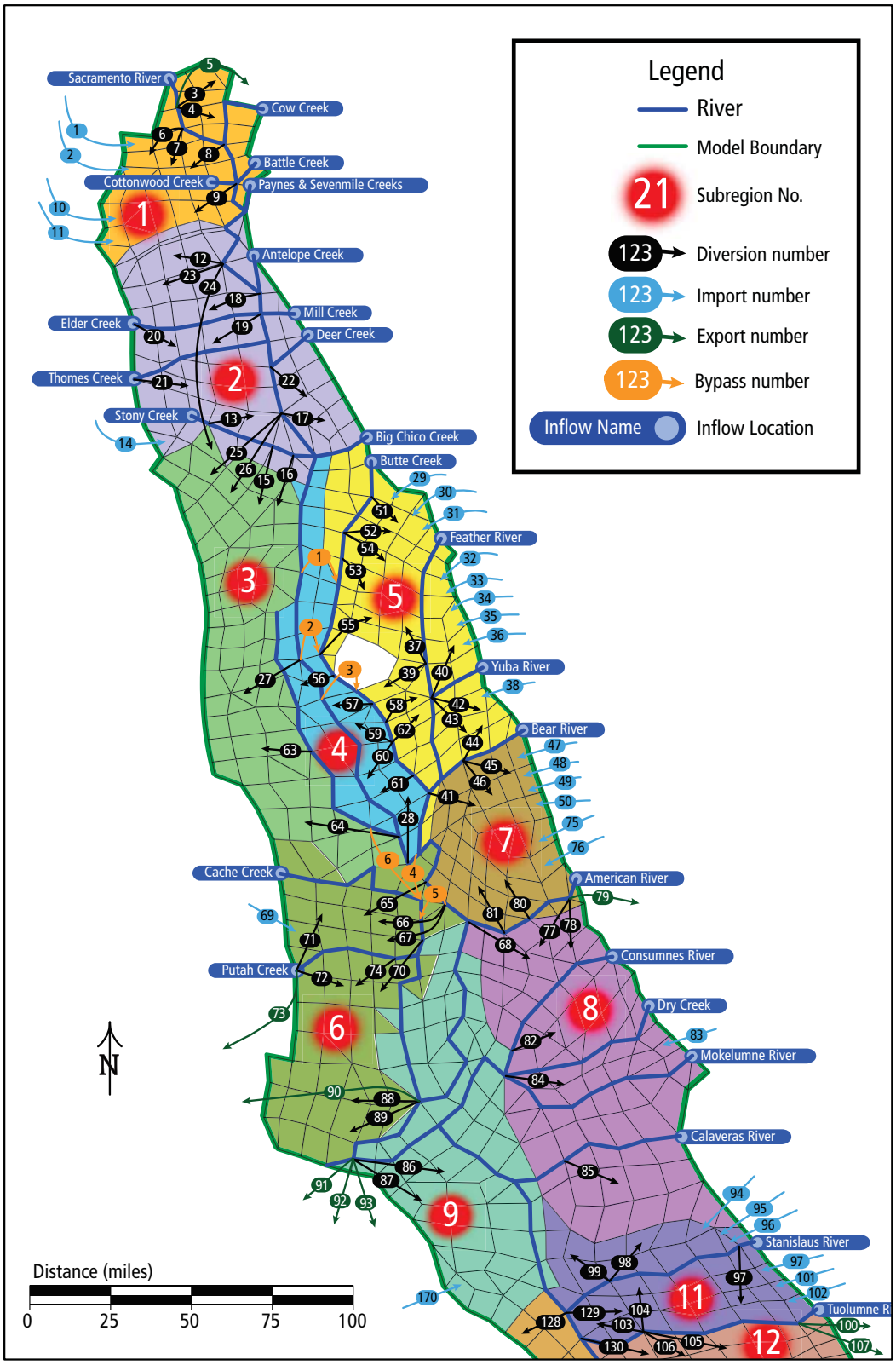


Figure 17B. C2VSim coarse grid with rim inflow, surface water diversion and surface water bypass locations.

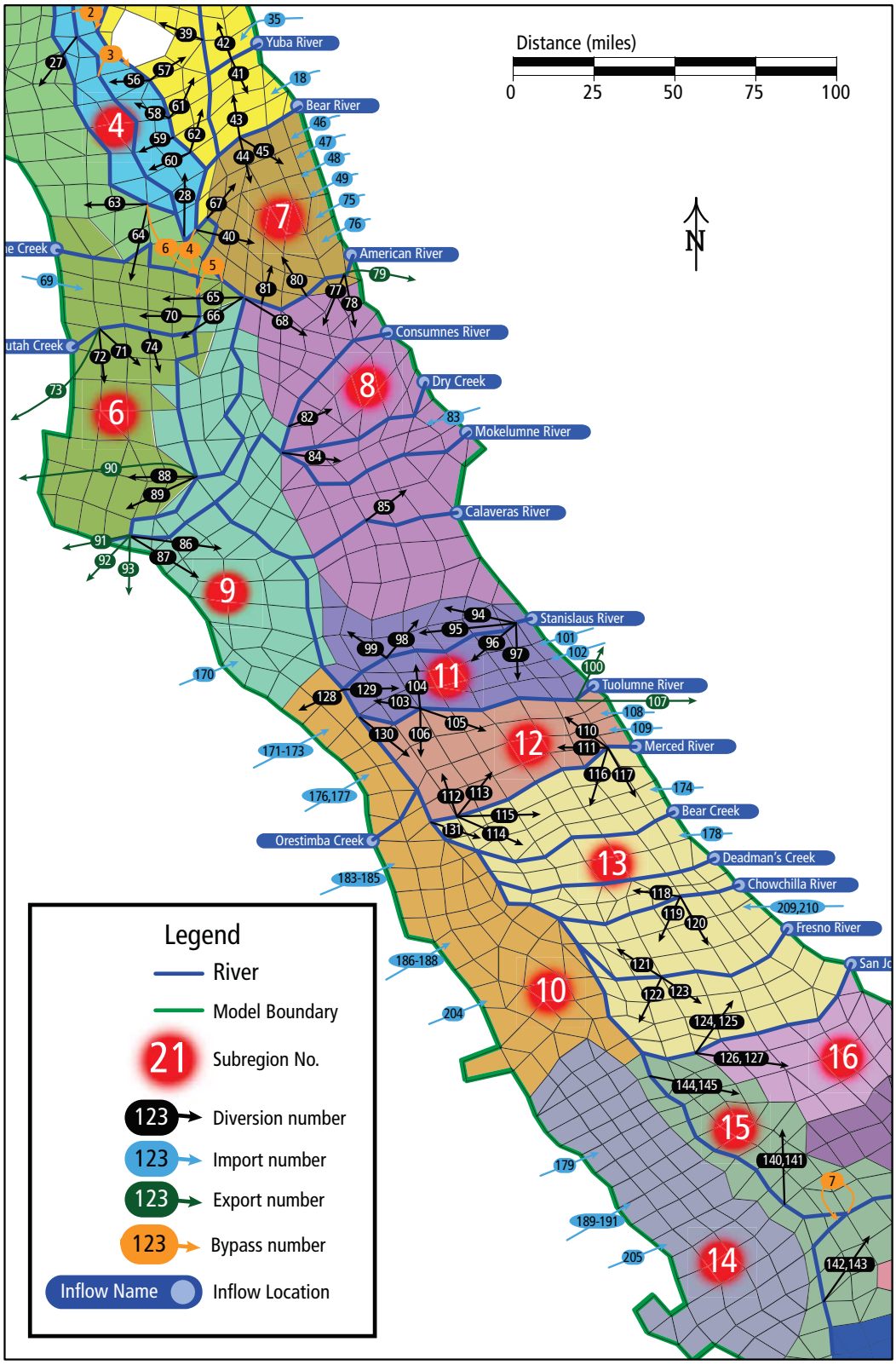
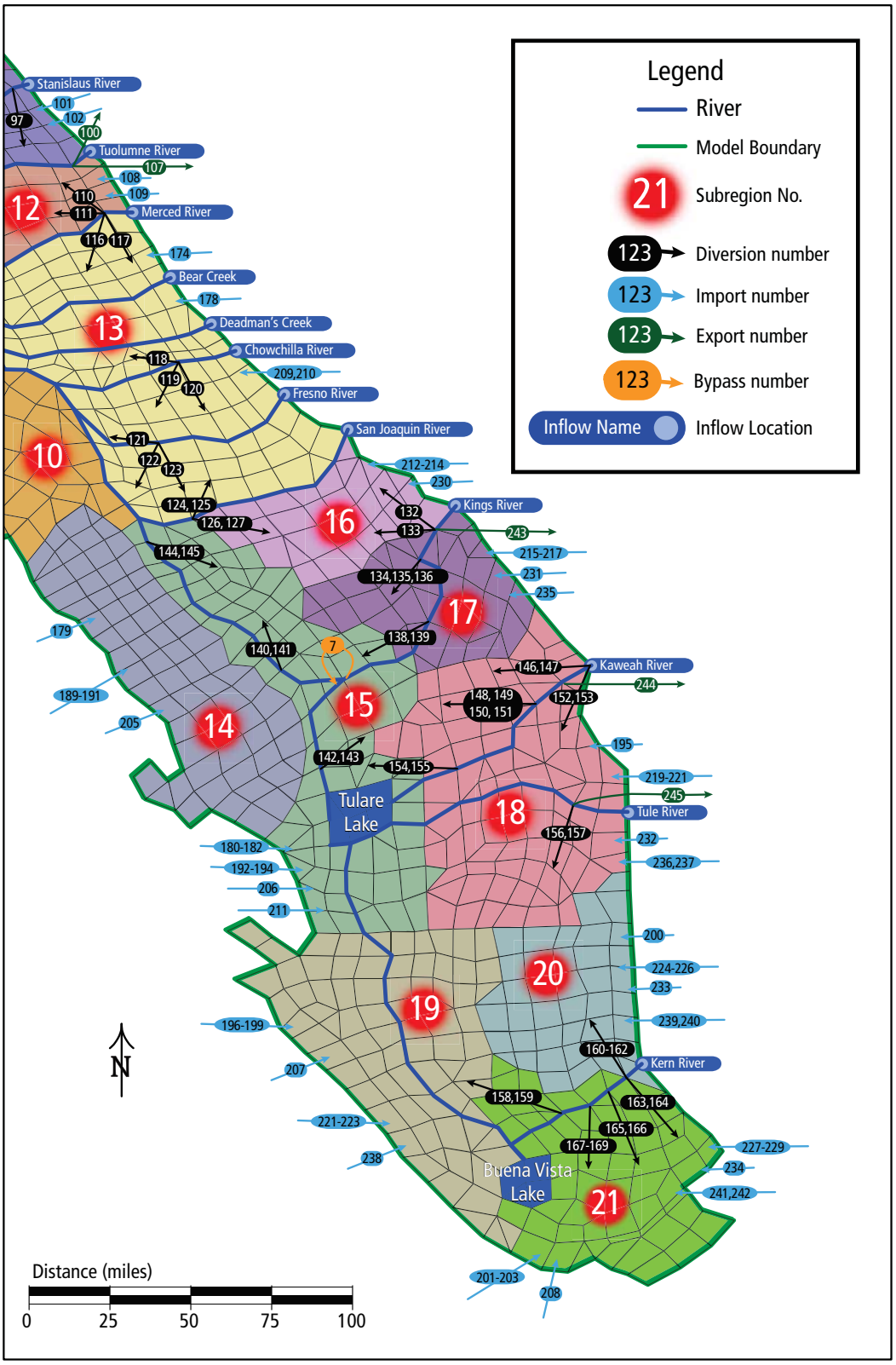


Figure 17C. C2VSim coarse grid with rim inflow, surface water diversion and surface water bypass locations.



Diversions

The C2VSim model surface water diversion database contains historical deliveries for 243 surface water diversions. Each diversion is described in detail in the companion report *Historical Rim Inflows, Surface Water Diversions and Bypass Flows* (Brush, 2012). These diversions are divided into five classes according to the end use: agricultural, urban, refuges, aquifer storage, and canal seepage. Within the Land Use Process, agricultural diversions are used to meet agricultural demands and urban diversions are used to meet urban demands. Refuge diversions are listed separately in the diversions database, but are used to meet the agricultural demands because there is no separate refuge class. Aquifer storage diversions represent water that is diverted to highly permeable areas, which is simulated by using a large recoverable loss coefficient to allocate this water to aquifer recharge. Canal seepage diversions represent time series of estimated seepage on large canals that was derived from studies, which is also simulated by using a large recoverable loss coefficient to allocate this water to aquifer recharge.

The C2VSim model simulates diversions from river nodes contained within the model boundary and from areas located outside the model boundary. Diversions from areas located outside the model boundary are called imports. Imports include diversions from large canals such as the Friant-Kern Canal, the California Aqueduct, and the Cross-Valley Canal, and many smaller canals. The locations of individual surface water diversions and the general locations of surface water imports are shown in Figure 17. Sources for these time series are detailed in the companion report, *Historical Rim Inflows, Surface Water Diversions and Bypass Flows* (Brush, 2012).

Water losses to evaporation, evapotranspiration and canal leakage can occur between the diversion point and the final delivery point. IWFM simulates canal leakage as 'recoverable losses' and evaporation and evapotranspiration as 'non-recoverable losses', For most surface water diversions, the recoverable loss and non-recoverable loss are expressed as a constant percentage of the total diversion amount. Surface water diversions to aquifer storage programs are routed directly to the aquifer by specifying the sum of the recoverable and non-recoverable losses as 100%. Ten surface water diversions that simulate seepage on sections of the California Aqueduct and Friant-Kern Canal utilize time series of seepage rates and recoverable losses of 100%.

Bypasses

IWFM uses bypasses to route surface water between two river nodes that are not directly connected in the river network. Each bypass can be specified with either a time series of monthly flow values or a rating table. The C2VSim model includes 11 surface water bypasses (Figure 17). Five bypasses use historical time series to simulate the operation of weirs that route flood flows in the Sacramento River Basin: Moulton Weir, Colusa Weir, Tisdale Weir, Fremont Weir and Sacramento Weir. One bypass uses a historical time series to simulate the Knights Landing Ridge Cut flows to the Yolo Bypass. One bypass uses a historical time series to simulate the Kings

River bifurcation, routing water to the South Fork Kings River at the Army Weir. Four bypasses simulate aquifer storage programs on the Kaweah River, Tule River, South Fork of the Kings River and the Kern River Flood Channel. One bypass uses a historical time series (currently set to zero owing to a lack of data) to route water from the Kern River flow to Buena Vista Lake. Sources for these time series are detailed in the companion report, *Historical Rim Inflows, Surface Water Diversions and Bypass Flows* (Brush, 2012).

Lakes

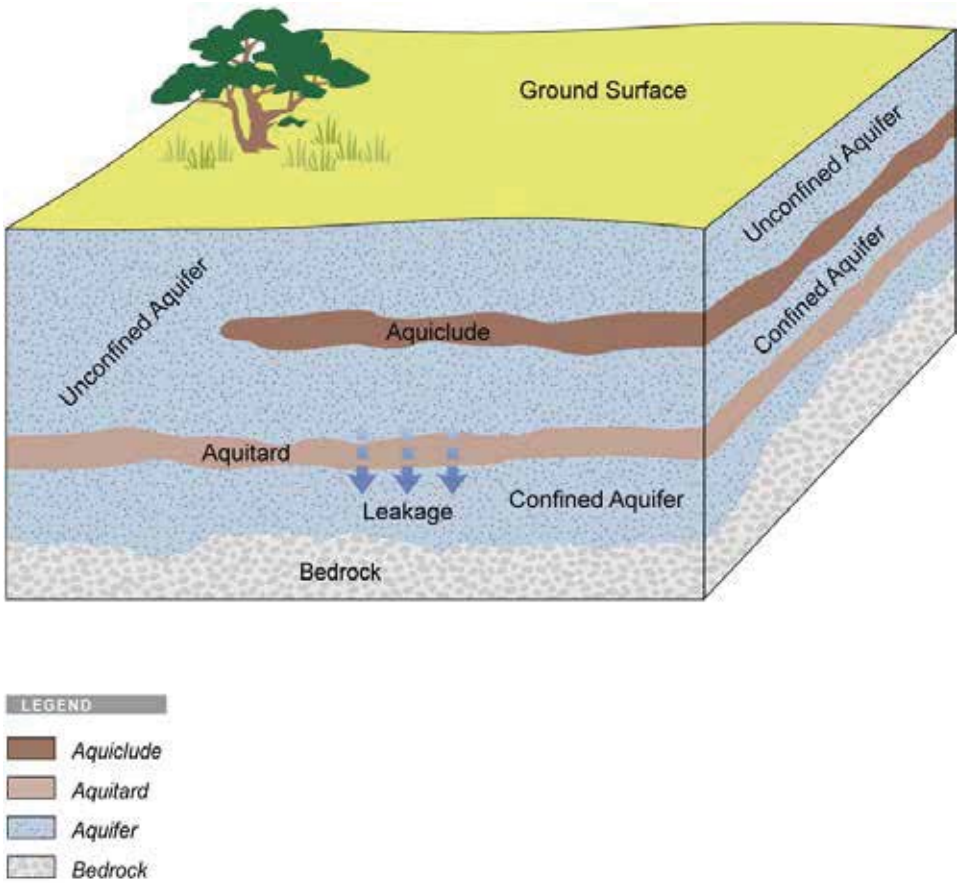
The C2VSim model includes two lakes, Buena Vista Lake and Tulare Lake, described above. Buena Vista Lake is simulated with four model elements, and can exchange water vertically with the groundwater flow system. It receives water from precipitation and through a bypass from the Kern River. Water leaves Buena Vista Lake through evapotranspiration and, if the lake surface altitude is greater than 321 ft, through discharge to the Kern River Flood Channel. Tulare Lake is simulated with six model elements, and can also exchange water vertically with the groundwater flow system. It receives water from precipitation and from outflow of the Kaweah River, the Tule River, the South Fork of the Kings River and the Kern River Flood Channel. Water leaves Tulare Lake through evapotranspiration and, if the lake altitude is greater than 206 ft, to the North Fork Kings River (Figure 13).

Groundwater Flow Process

The IWFM Groundwater Flow Process simulates horizontal and vertical flows in a multi-layer aquifer system that can include a combination of unconfined, confined and leaky aquifers, aquicludes and aquitards (Dogrul, 2012A) (Figure 18). Aquifers can also change between confined and unconfined as aquifer heads fluctuate. Three-dimensional flow is accomplished using a quasi-three-dimensional approach, with the spatial domain discretized in the horizontal direction using the Galerkin finite element method. For each time step, a two-dimensional groundwater head field is computed for each aquifer layer using the depth-integrated groundwater flow equation, and vertical flow is then computed through approximated leakage terms.

The Groundwater Flow Process balances inflows and outflows, and manages water storage within each element and layer. Inflows include vertical inflow from the unsaturated zone above, recharge through recoverable loss associated with diversion and bypass canals, and boundary flows and percolation from small-stream watersheds. Outflows include discharges to pumps and tile drains. Water can also flow to and from rivers and lakes.

Figure 18. IWFM groundwater flow process.



Pumping

IWFM allows groundwater pumping to be simulated as either well pumping or elemental pumping. For the C2VSim model, the well pumping functionality is used for all groundwater pumping for urban usage, and elemental pumping is used for all groundwater pumping for agricultural usage. 133 wells were specified for the C2VSim model for urban groundwater pumping. These wells were placed in groundwater-dependent population centers in each model subregion (Figure 19). For each time step, the C2VSim model calculates the total urban water demand for each subregion, subtracts the available surface water for each subregion, and allocates any remaining urban water demand within each subregion among the specified urban wells assigned to that subregion.

Agricultural pumping is allocated to elements (Figure 20) and then to layers within each element using a set of pumping specification tables, which remain fixed throughout the simulation. Each time step, the C2VSim model calculates the total agricultural water demand for each subregion, subtracts the available surface water for each subregion, and uses the pumping specification tables to allocate any remaining agricultural water demand among elements and aquifer layers. The spatial distribution of agricultural pumping in the CVGSM model was based on that developed for the CV-RASA model by Diamond and Williamson (1983). This distribution was largely maintained in the C2VSim model for subregions 2-13 and 15-18. The spatial distribution of agricultural pumping in subregions 1, 14 and 19-21 were estimated by DWR staff based on the difference between estimated agricultural water demands and estimated surface water supplies (CH_2M Hill, Inc., and S.S. Papadopoulos and Associates, 2006). The vertical agricultural pumping distribution within each element was taken from the CV-RASA model (Williamson et al., 1989).

Tile Drains

The CVGSM model included 90 general head boundary conditions in the top model layer to simulate tile drains located along the west side of the San Joaquin Valley. These included on-farm tile drains installed over a period of many years that are still in operation, and a regional tile drain system installed in the Westlands Water District that operated for only a short period of time. IWFM provides a separate tile drain function which facilitates delineation and calibration of tile drains. However, the current version of the IWFM requires tile drains to be operational for the entire simulation period. Therefore, only the on-farm tile drains outside the Westlands Water District were retained in the C2VSim model (Figure 21), and these are operational for the entire simulation time period. This may limit the accuracy of the groundwater heads and tile drain discharges in this portion of the model area. Tile drains that could be operated for specified time periods would improve the accuracy of the model in this area.

Figure 19. Urban well locations in the C2VSim model.

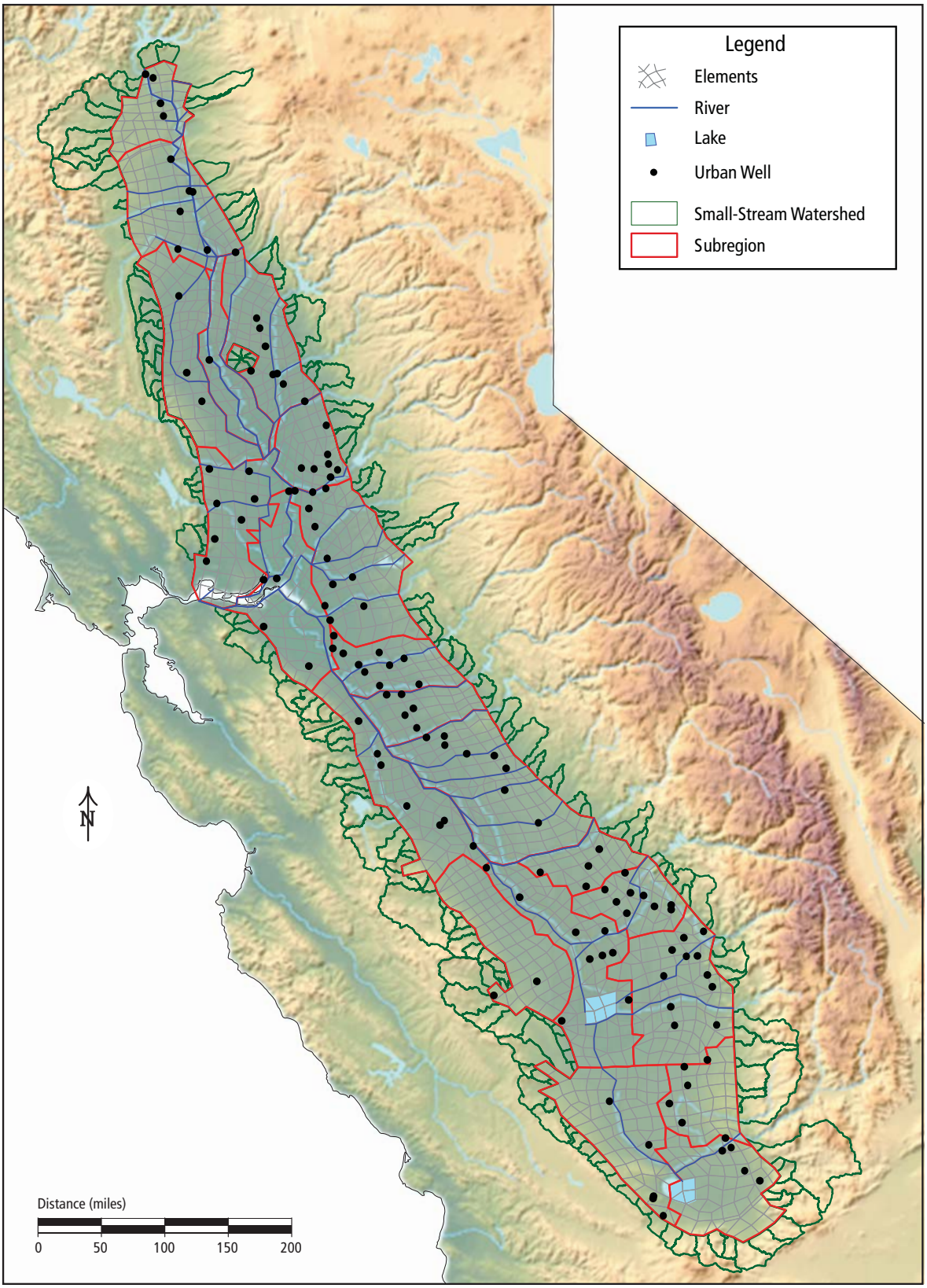


Figure 20. C2VSim agricultural pumping distribution.

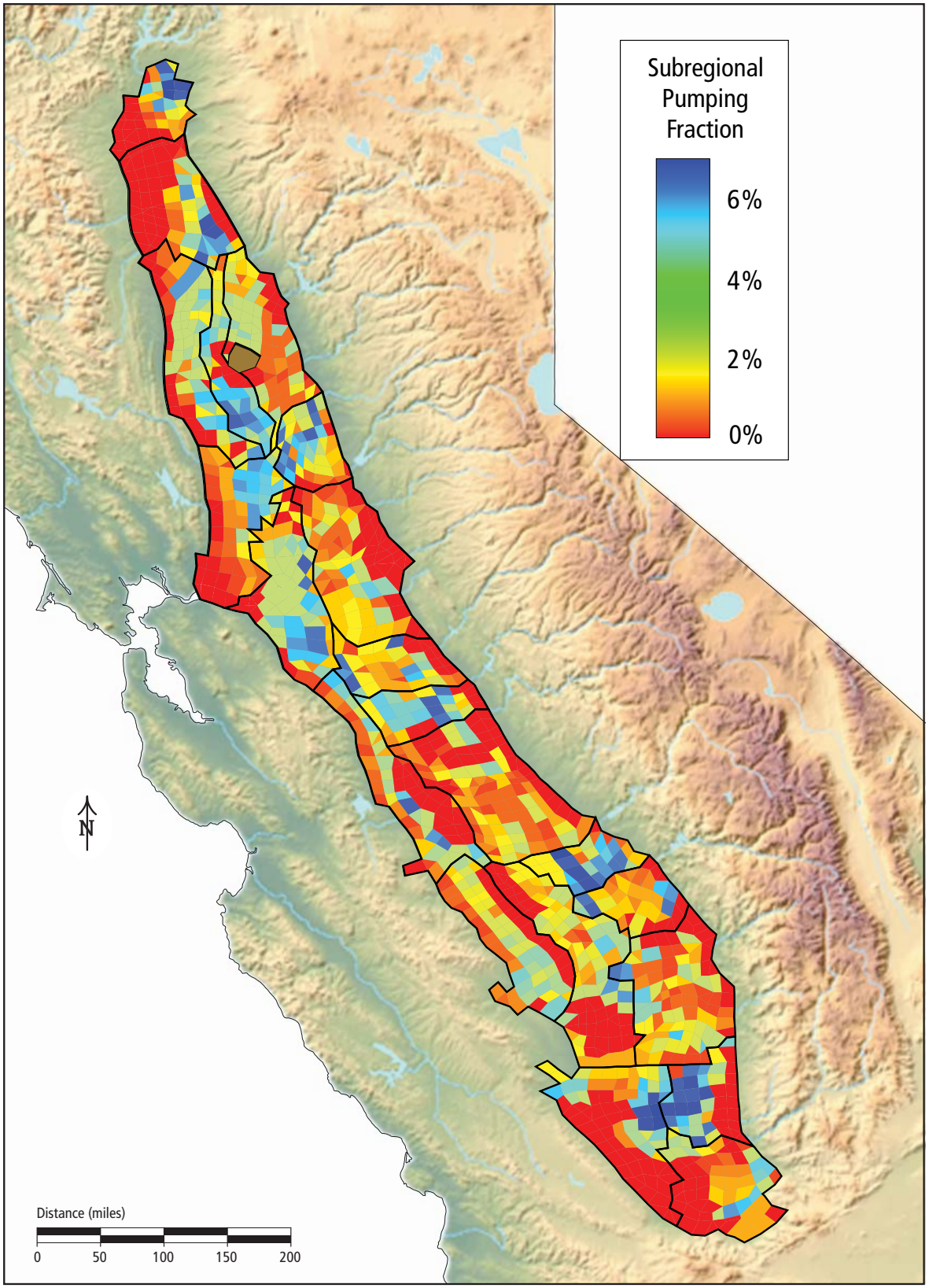
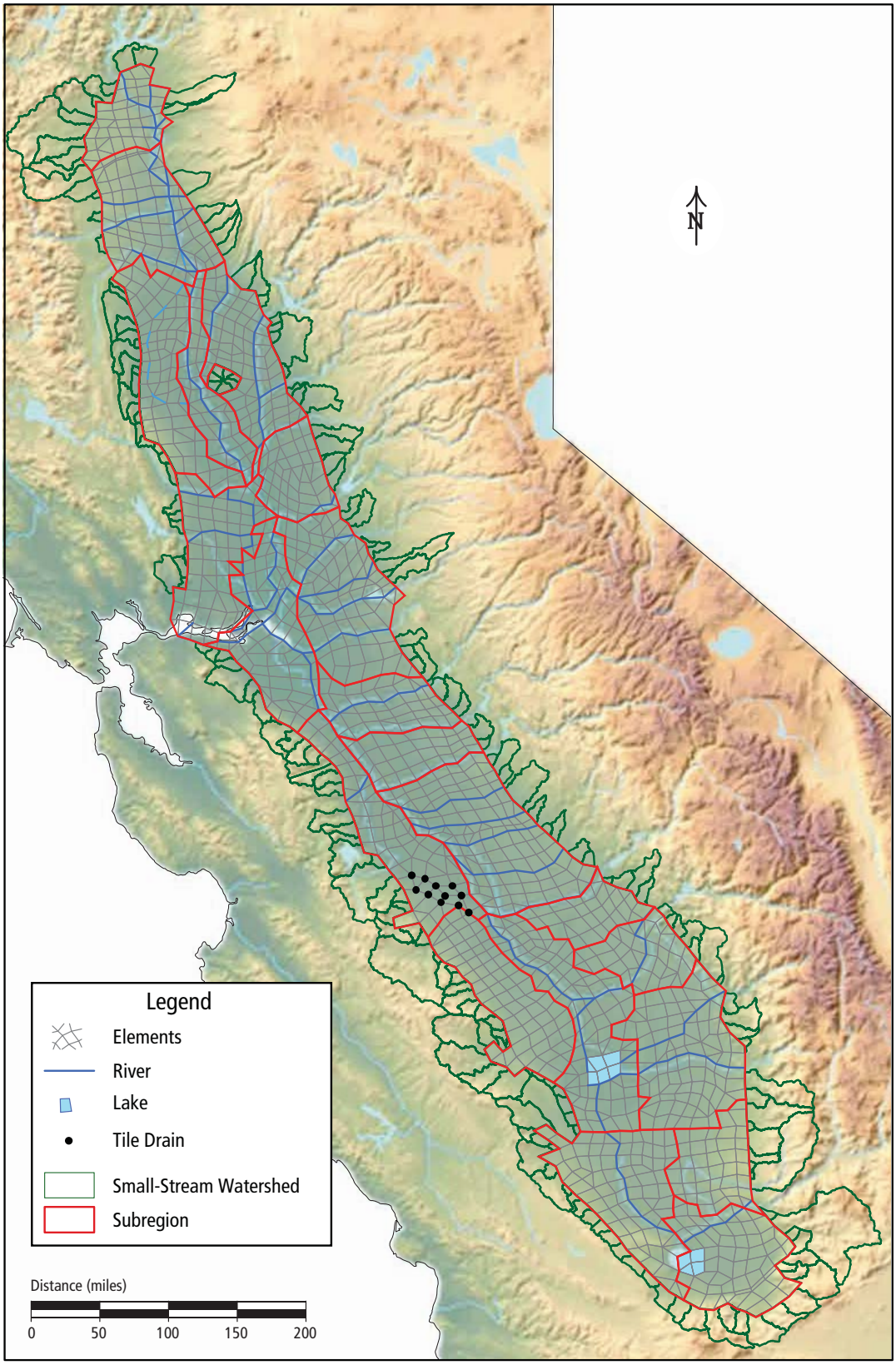


Figure 21. C2VSim coarse grid with tile drain locations.



Small-Stream Watersheds

A significant portion of the water that flows through the Central Valley originates in the rim watersheds up-gradient from the alluvial portion of the valley. Within the C2VSim model, these rim watersheds can be divided into two broad classes: gauged watersheds with specified inflows into the C2VSim stream network, and ungauged watersheds whose outflow is dynamically calculated using the IWFM Small-stream Watershed component. The land cover in these watersheds is generally native vegetation. The watersheds receive precipitation and discharge surface water into small and intermittent streams that flow across the valley floor into larger streams and rivers, with a portion of this flow entering the aquifer as recharge. They also discharge a small amount of groundwater laterally into the Central Valley aquifers. The IWFM Small-stream Watershed component dynamically calculates these monthly surface water discharge, recharge, and subsurface groundwater flow values. The C2VSim model includes 210 small stream watersheds, covering an area of 7,940 square miles.

The small-stream watersheds in the C2VSIM model were delineated using the California Interagency Watershed Map of 1999 (CalWater 2.2.1, http://www.ca.nrcs.usda.gov/features/calwater/). First, the portion of the CalWater coverage ultimately draining to the Carquinez Strait was isolated. A union was then performed between this coverage and the C2VSim finite element grid coverage using ArcGIS to obtain the portion of CalWater that drained to the Carquinez Strait and was not coincident with the C2VSim finite element grid. The watersheds in this remaining coverage were then divided into those draining to simulated streams with gauged inflows, and those draining directly to the area covered by the C2VSim finite element grid; this second group comprised the watersheds to be simulated as small-stream watersheds.

The subwatersheds derived from the CalWater coverage were aggregated and allocated to the C2VSim model node nearest to the point where their discharge stream enters the domain of the C2VSim finite element grid. This produced 210 small stream watersheds. Stream arcs comprising the minor or intermittent streams that drain these small-stream watersheds were then delineated to flow through the C2VSim nodes that most closely matched the natural watercourses, to the point where they terminated in simulated streams.

Monthly precipitation for the centroid of each small stream watershed was derived from a 2 km x 2 km precipitation dataset for the State of California obtained from the PRISM group at the University of Oregon. Monthly evapotranspiration rates for native vegetation for each small stream watershed were assumed to be equal to the values of the adjacent C2VSim model subregion (see Figure 12).

Initial Conditions

The initial condition for the C2VSim simulation includes the head for each model node and layer (Figure 22); soil moisture conditions for each soil type in each subregion the unsaturated zone for each model element, and each small-stream watershed; the water level in each lake; and the interbed thickness and preconsolidation head for each model node and layer. The initial heads were based on maps of groundwater heads developed by Bryan (1923) and California Department of Public Works (undated); in areas with no data, initial heads were determined by setting the water table to 25 ft below the land surface and then running the model for five years to calculate stable initial groundwater heads. The initial soil moisture conditions were estimated by setting all moistures to zero, running the model for five years, and using the resulting soil moistures for the end of September. These values were found to be relatively stable from year to year. The preconsolidation heads and initial interbed thicknesses were derived from the CVGSM model.

Figure 22A. Initial water table altitude for the C2VSim model, October 1, 1921.

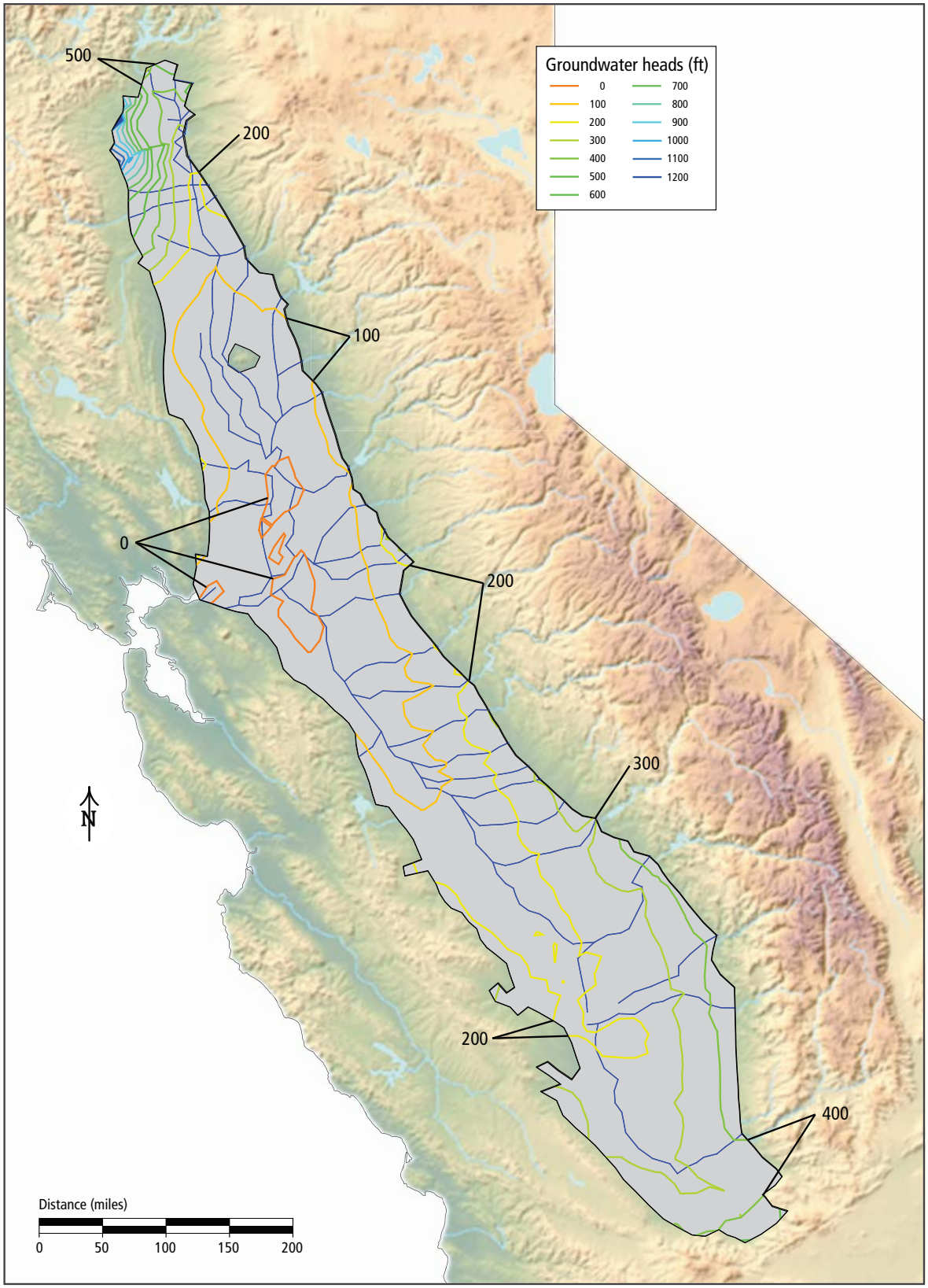


Figure 22B. Initial heased for C2VSim model layer 2, October 1, 1921.

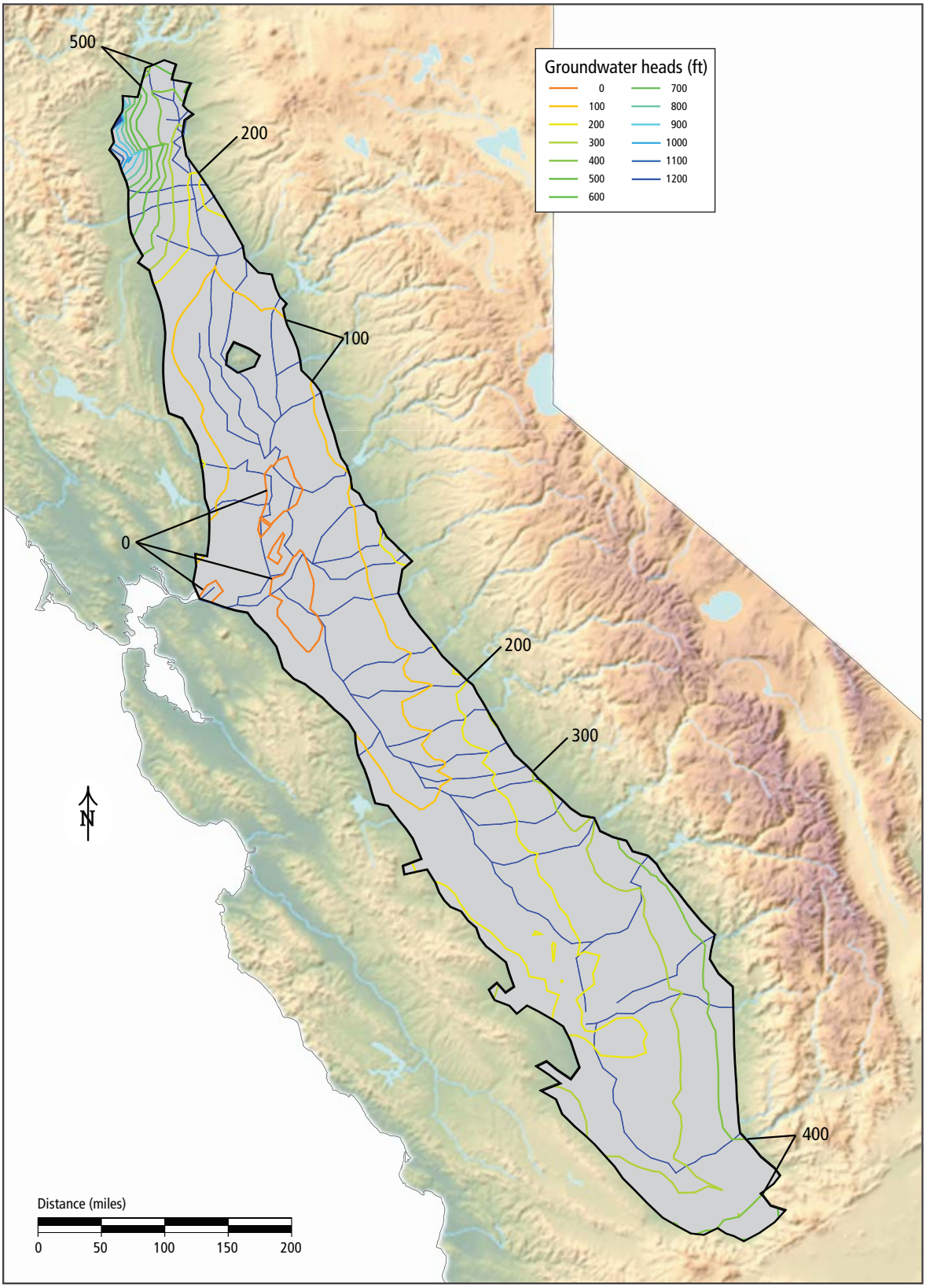
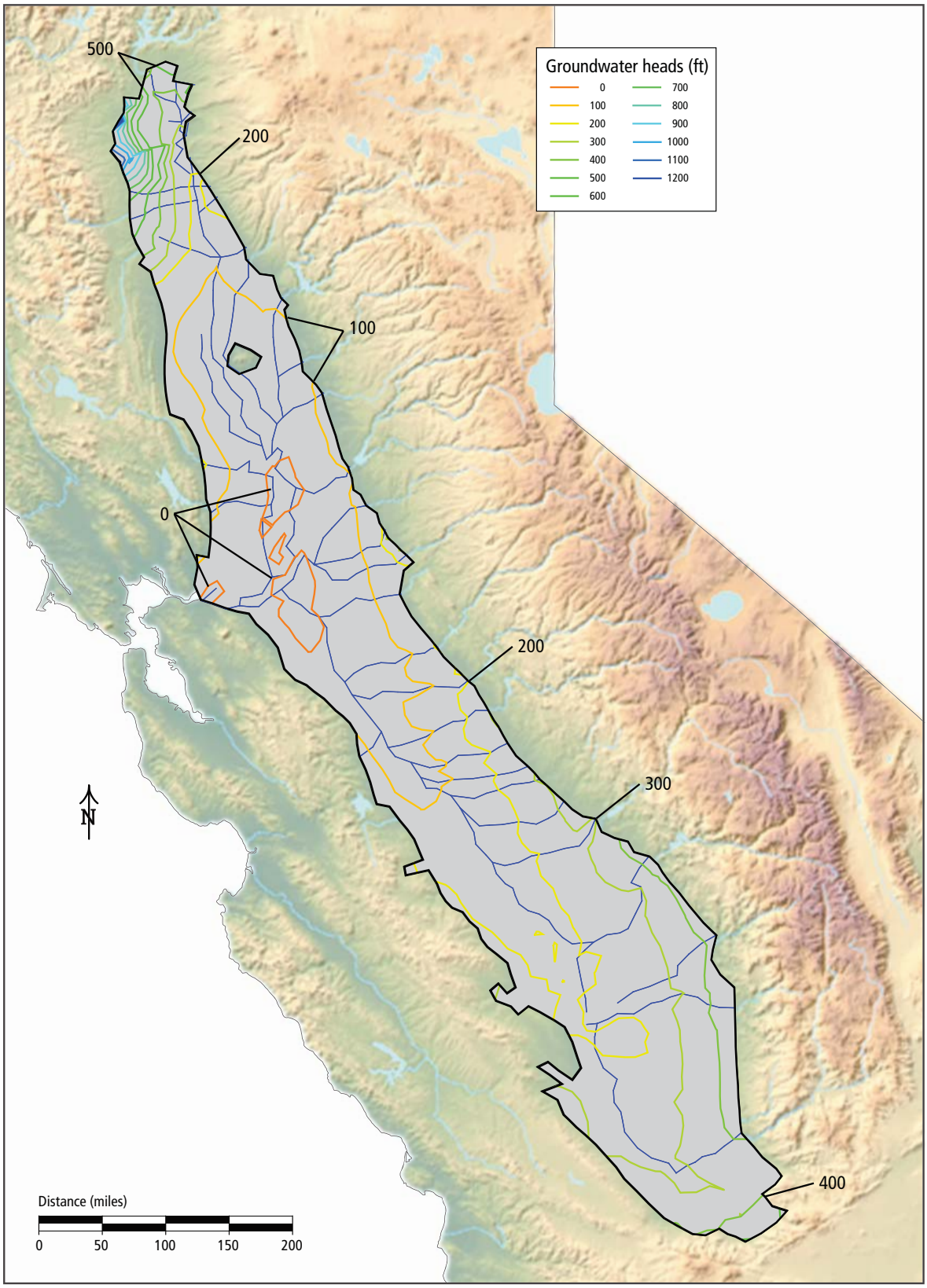


Figure 22C. Initial heads for C2VSim model layer 3, October 1, 1921.



Calibration

The C2VSim model includes many parameters, some of which were estimated prior to model calibration, and some of which were adjusted during model calibration. In general, soil types at each element and parameters that partition water between different water budget components were estimated prior to model calibration, and parameters related to the hydrologic properties of the groundwater flow system, rivers and lakes were adjusted during model calibration.

Estimated Parameters

IWFM requires many parameters that describe how water is to be routed or allocated during water budget calculations. Parameters used in water budget calculations include soil properties (field capacity, total porosity, hydraulic conductivity and curve number), re-use factors, urban water use factors, crop water use parameters, and crop root zone depths. The parameters related to the soil type are used to partition precipitation into runoff and infiltration. Re-use factors quantify the degree to which agricultural and urban return flows are used within each model subregion. Urban water use factors quantify the partitioning between indoor and outdoor area and the destination of urban return flows within each subregion. Crop water use parameters are used in the calculation of agricultural water demands. The values of these parameters were determined before model calibration.

Each model element is assigned a soil type between 1 and 4. The soil type quantifies the runoff potential of the soil. In the USDA soil classification system, soils with a low runoff potential are classed as A and those with a high runoff potential are classed as D, with intermediate soils classed as B and C. In IWFM, these are converted to integer values, with A=1, B=2, C=3 and D=4. The USDA Soil Survey Geographic (SSURGO) Database (2004A) was used to determine the average soil class for each model element, and the USDA State Soil Geographic (STATSGO) Database (1997) was used for areas where the SSURGO data was not available (Figure 23).

The C2VSim model includes a time series of agricultural and urban re-use factors for each model subregion (Table 4). These factors specify the fraction of surface runoff from applied water that is re-used within each model subregion. Although IWFM allows each of these factors to vary through time, they are held constant in the C2VSim model.

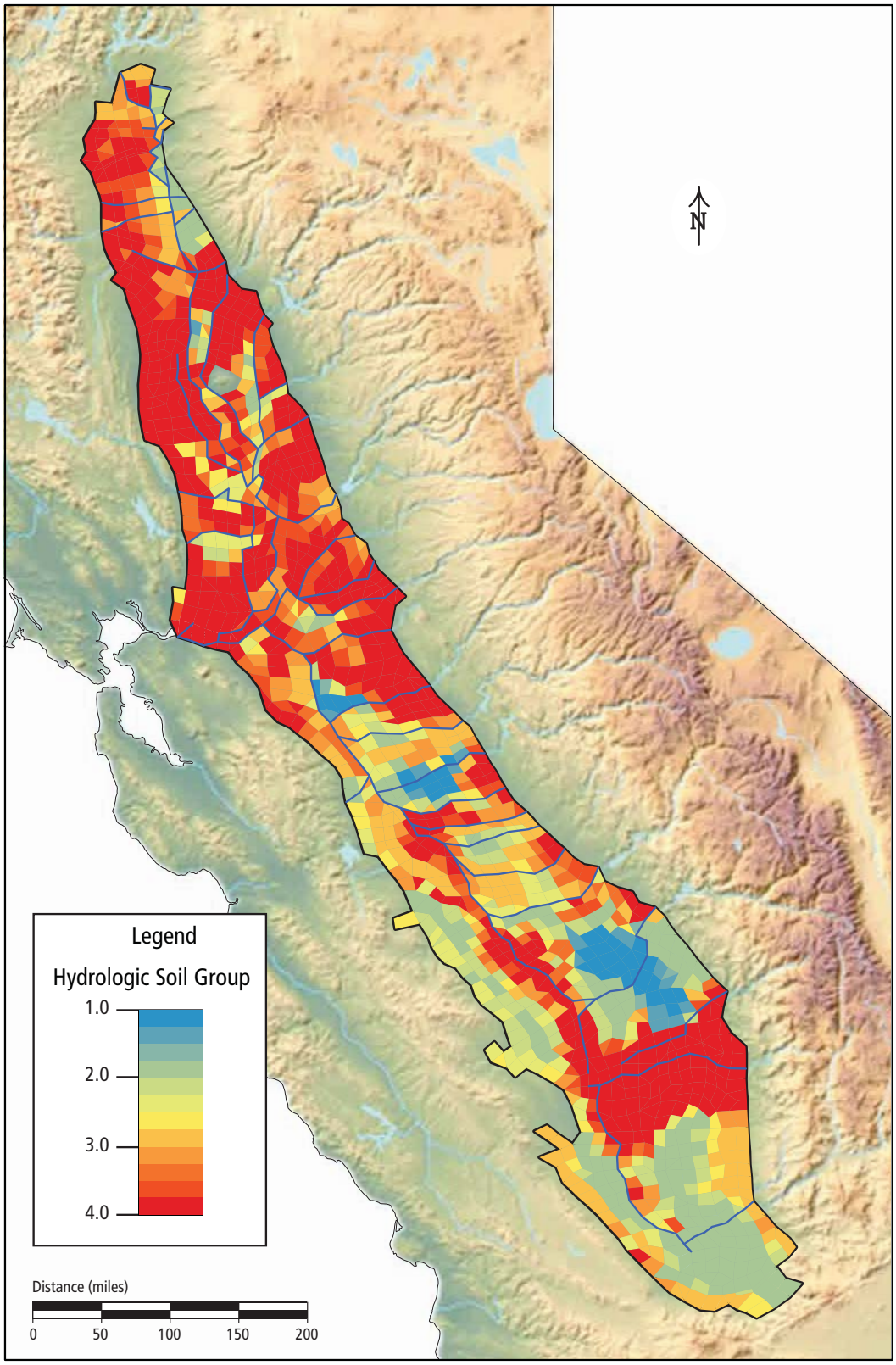
Urban return flow parameters specify whether urban return flows go into groundwater recharge or into rivers. In the C2VSim model, all urban return flows go into rivers for subregions 1-9 and into groundwater recharge for subregions 10-21. The fraction of pervious area to total area is assumed to be 62%.

Aggregate crop water demands for each subregion are calculated dynamically by IWFM. Two monthly crop demand parameters for each crop are used in this calculation: the minimum soil moisture requirement for each crop specified as a

Table 4. Water re-use factors for C2VSim model subregions.

Subregion	Re-use factor
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

Figure 23. Hydrologic soil group for each C2VSim coarse-grid model element.



fraction of field capacity, and the crop efficiency. These values were derived from the DWR Consumptive Use model (DWR, 1979).

Calibration Methodology

The C2VSim model is a highly parameterized integrated hydrologic model, and thus a specialized approach must be used to calibrate the model parameters. A simple model with few parameters can be calibrated by adjusting individual parameter values up and down until the model produces simulated output that corresponds reasonably well with observed values. However, for a highly parameterized model like C2VSim, this approach is impractical. Instead, a mathematical approach such as regularized inversion can be used to combine many observations into an objective function and then adjust many parameters at one time (Doherty and Hunt, 2010).

The C2VSim model's hydrogeologic parameters were calibrated using Parameter ESTimation (PEST) tool, a model-independent software suite for parameter estimation and uncertainty analysis for complex and highly parameterized models (Doherty, 2004). PEST was used to automate some aspects of model calibration, running the C2VSim model many thousands of times with slightly different sets of input parameters, analyzing the model results after each run, and adjusting parameter values to achieve a slightly better fit to observed values. The C2VSim model parameters calibrated using PEST included the hydraulic conductivities and storage parameters at each groundwater node, the curve numbers and soil conductivities for each subregion, river-bed conductances for each river node, and horizontal hydraulic conductances for the White Wolf Fault and the Red Bluff Arch. During calibration, all parameters were bounded within reasonable ranges. In all, more than 25,000 individual parameters were calibrated.

The first step in model calibration was the development of a set of computer programs to link IWFM with the PEST programs (CH_2M Hill, Inc., and S.S. Papadopoulos and Associates, 2005). These programs write PEST instruction files, run the C2VSim model, and convert C2VSim output into a format that can be read and used by PEST. The C2VSim model was then calibrated in three phases. The first two calibration phases used pilot points to estimate parameter values at a reduced number of locations within the model domain, and spatial interpolation to assign values to model nodes (Doherty, 2003).

In the first phase, the model framework was thoroughly reviewed, values for estimated parameters were selected, and an initial observation data set was developed. 137 pilot points in the top two model layers (Figure 24A) and 40 pilot points in the bottom model layer (Figure 24B) were chosen in the interior of the model domain for calibrating aquifer parameters, 19 pilot points were chosen for calibrating the vertical hydraulic conductivity of the Corcoran Clay (Figure 24C), and parameter values were transferred from pilot points to model nodes using kriging (CH_2M Hill, Inc., and S.S. Papadopoulos and Associates, 2006).

In the second phase, the model framework was improved, a more extensive observation data set was developed, 394 pilot points coinciding with model nodes

Figure 24A. Pilot points used in phase one of C2VSim calibration, large set.

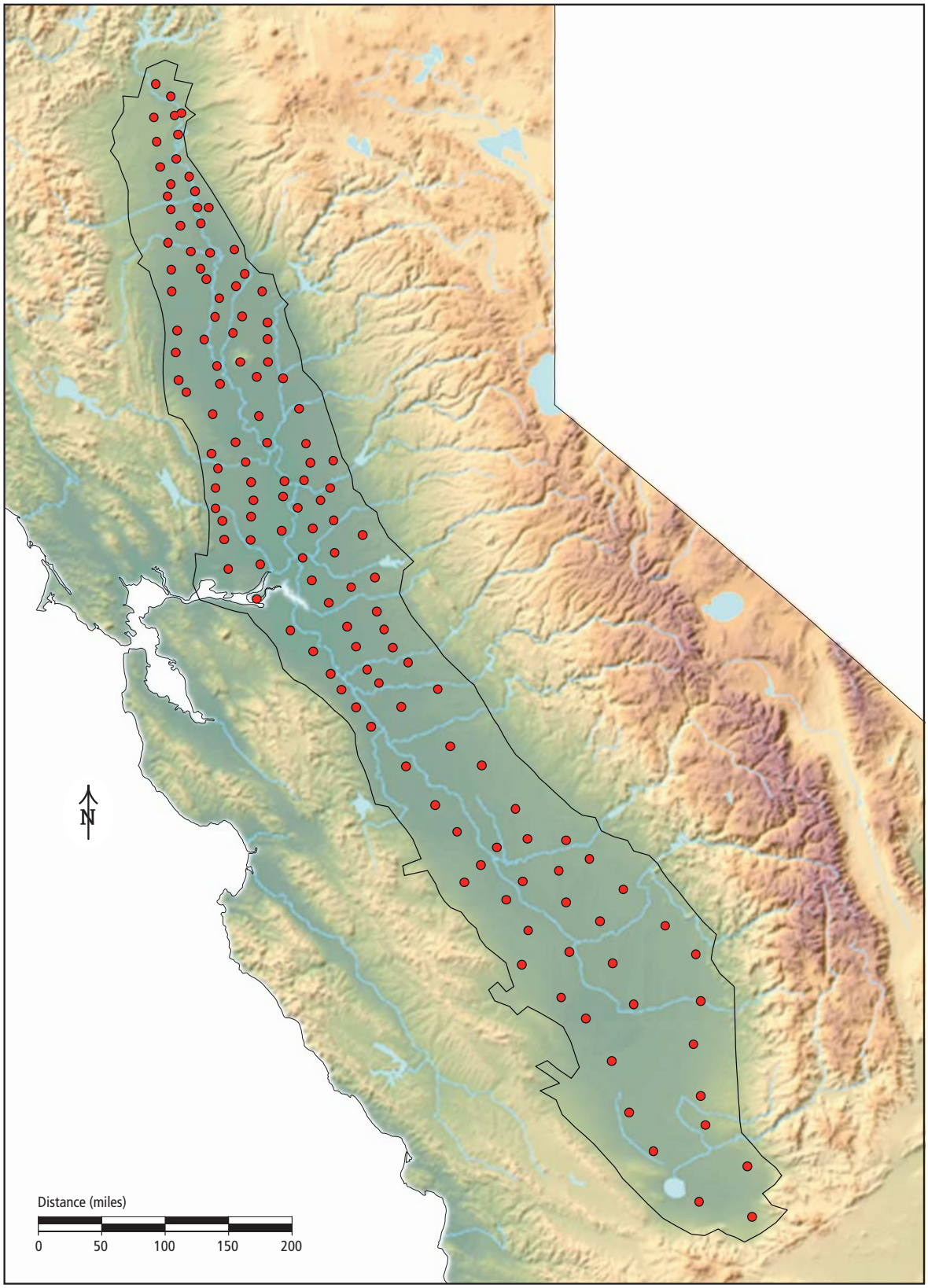


Figure 24B. Pilot points used in phase one of C2VSim calibration, small set.

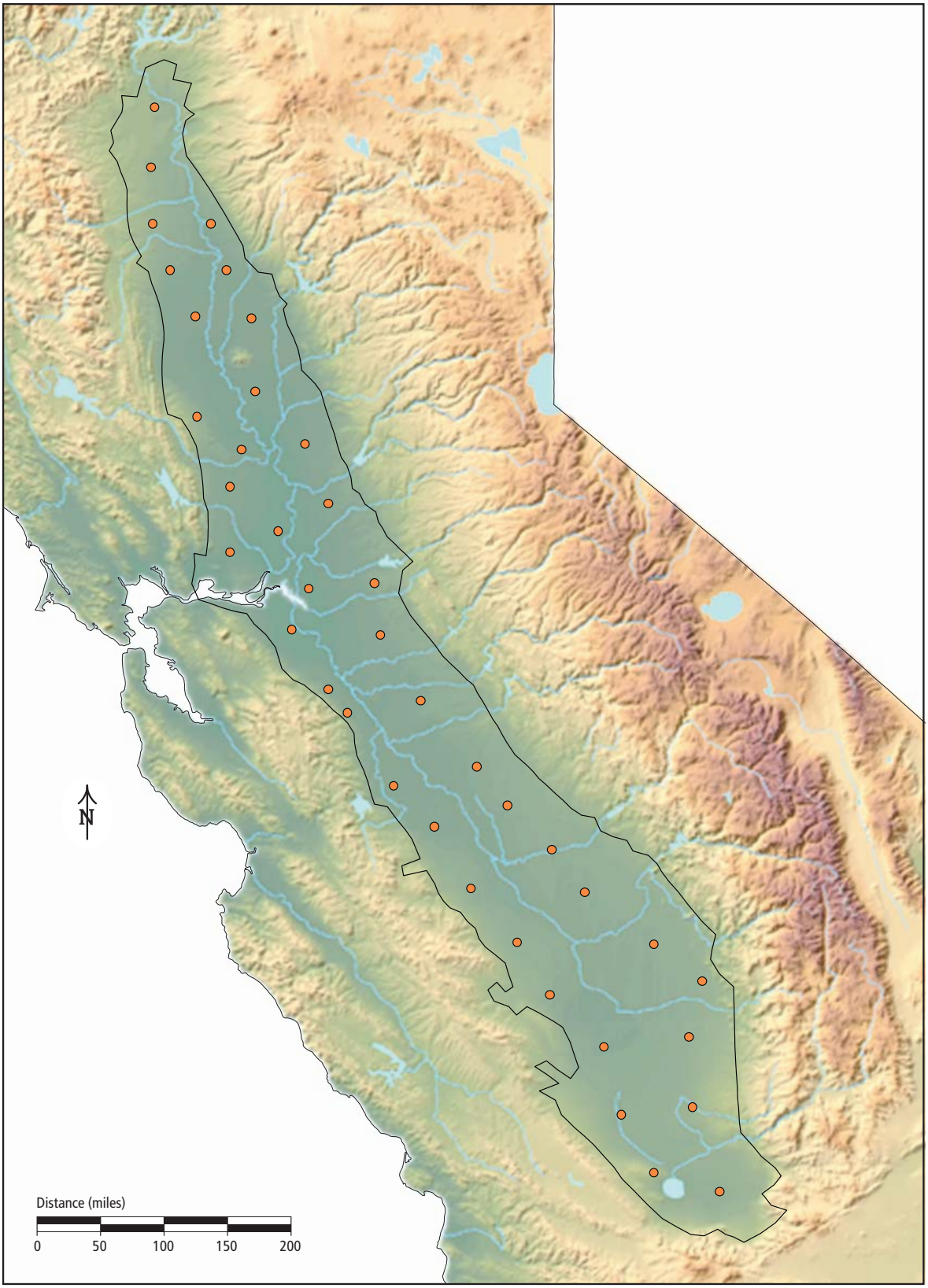
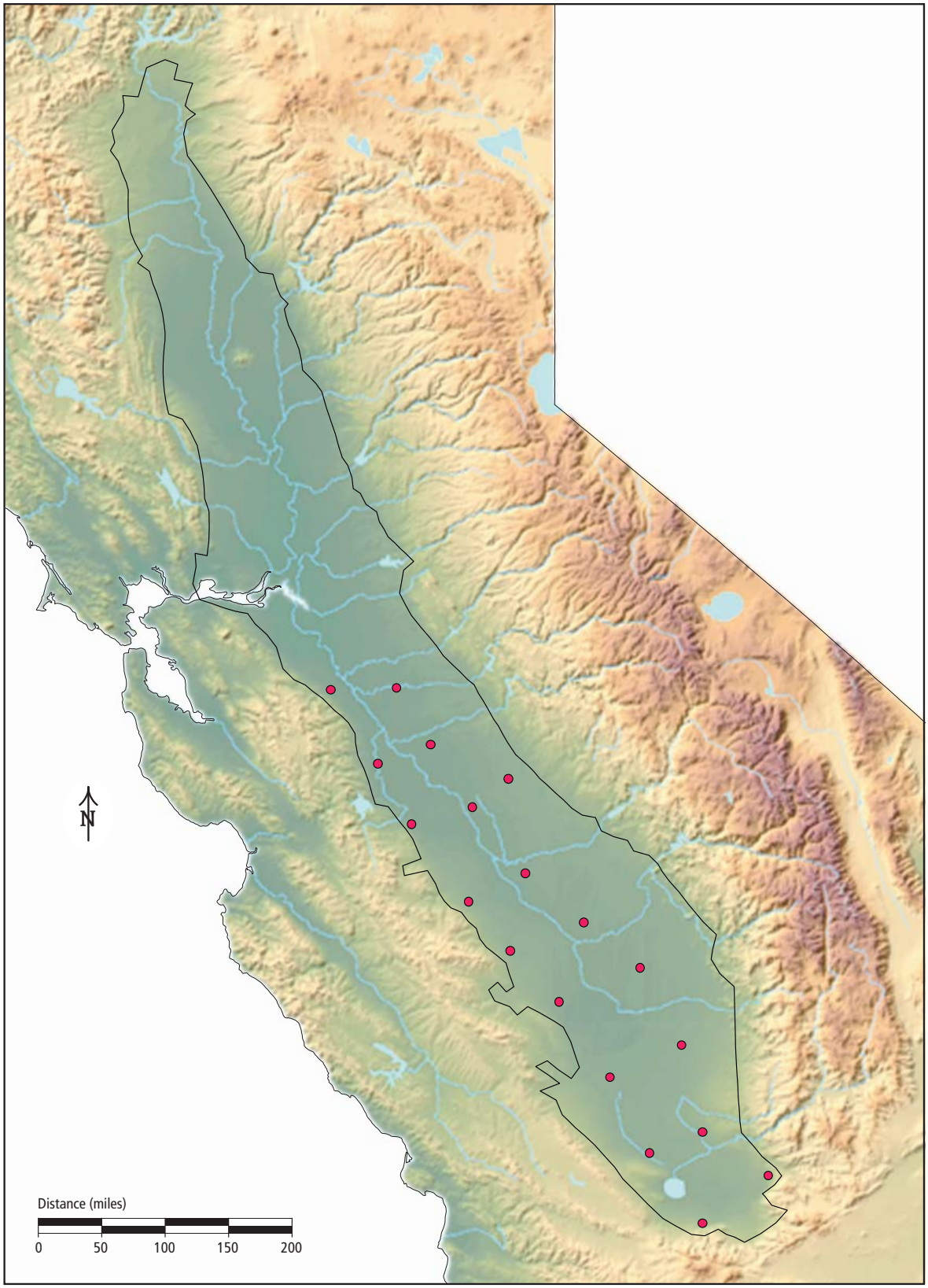


Figure 24C. Pilot points used in phase one of C2VSim calibration for the Corcoran Clay.



and encompassing the entire model domain were used for parameters in all model layers (Figure 25), and parameter values were transferred to the other model nodes using bilinear interpolation.

Computations for the first two phases were accomplished using Parallel PEST on networked PCs running Windows. In the third phase, the model input data was thoroughly reviewed and updated, the model framework was improved, and parameter values were calibrated directly for each model node. This was very computationally intensive, and was accomplished using BeoPEST (http://www.prinmath.com/pest/) under Linux on the Carver and Magellan supercomputers at the U.S Department of Energy's National Energy Research Scientific Computing Center (NERSC).

Calibration Targets

The initial phase of model calibration utilized a set of more than 23,000 calibration targets. This included groundwater heads, vertical groundwater head differences, river flows and average monthly groundwater-surface water flows. These observations were compiled in a PEST-readable format and were used to calibrate parameter values using the regional pilot points.

Groundwater observation wells were selected from a set of more than 17,000 wells in DWR's water-level database. 221 wells were selected that (a) had a single well screen that resides entirely in a single model layer; (b) has at least one water level measurement during or prior to 1977 and one water level measurement during or after 1997; and (c) no more than one well was selected in the same layer and model element (CH_2M Hill, Inc., and S.S. Papadopoulos and Associates, 2006). Water level observations were linearly interpolated to one value every six months so each observation well had two observations per year. Interpolation dates were selected to preserve periods of high and low water levels. Nine pairs of wells located near each other but in separate layers were used to create observed vertical head differences (Figures 26 and 27).

Monthly surface water flow observations were compiled at 22 locations for the period from October 1975 to September 1999. These observations were obtained from DWR's California Data Exchange Center (CDEC) and the USGS' National Water Information System (NWIS). Flow data were converted to units of acre-feet per month (Figure 28). Average observed groundwater-surface water flows were compiled for 33 river reaches. Mullen and Nady (1985) compiled annual water budgets for 1961 to 1977 for many Central Valley river reaches in support of the CV-RASA model. This period is different from the period chosen for calibration observations for the C2VSim model (1975-1999), and thus the average annual values were used and converted to units of acre-feet per month (Figure 29).

An expanded set of more than 73,000 calibration targets was developed for the local and nodal model calibration phases. This included groundwater heads, vertical groundwater head differences, small-stream watershed discharges, and land-surface subsidence. The river flow observations and average monthly groundwater-surface

Figure 25. Pilot points used in phase two of C2VSim calibration.

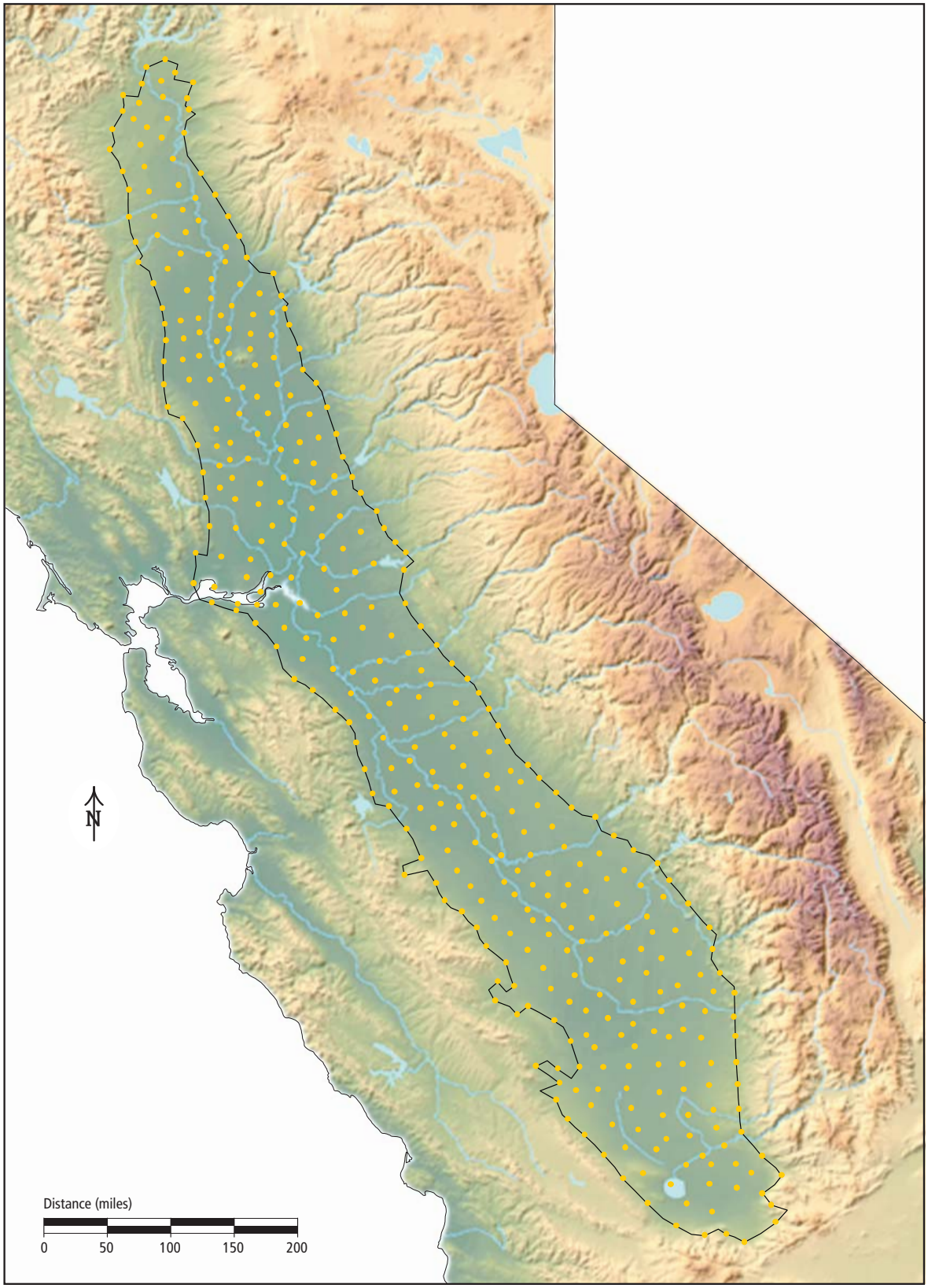


Figure 26. Observation wells for groundwater heads used in phase one of C2VSim calibration.

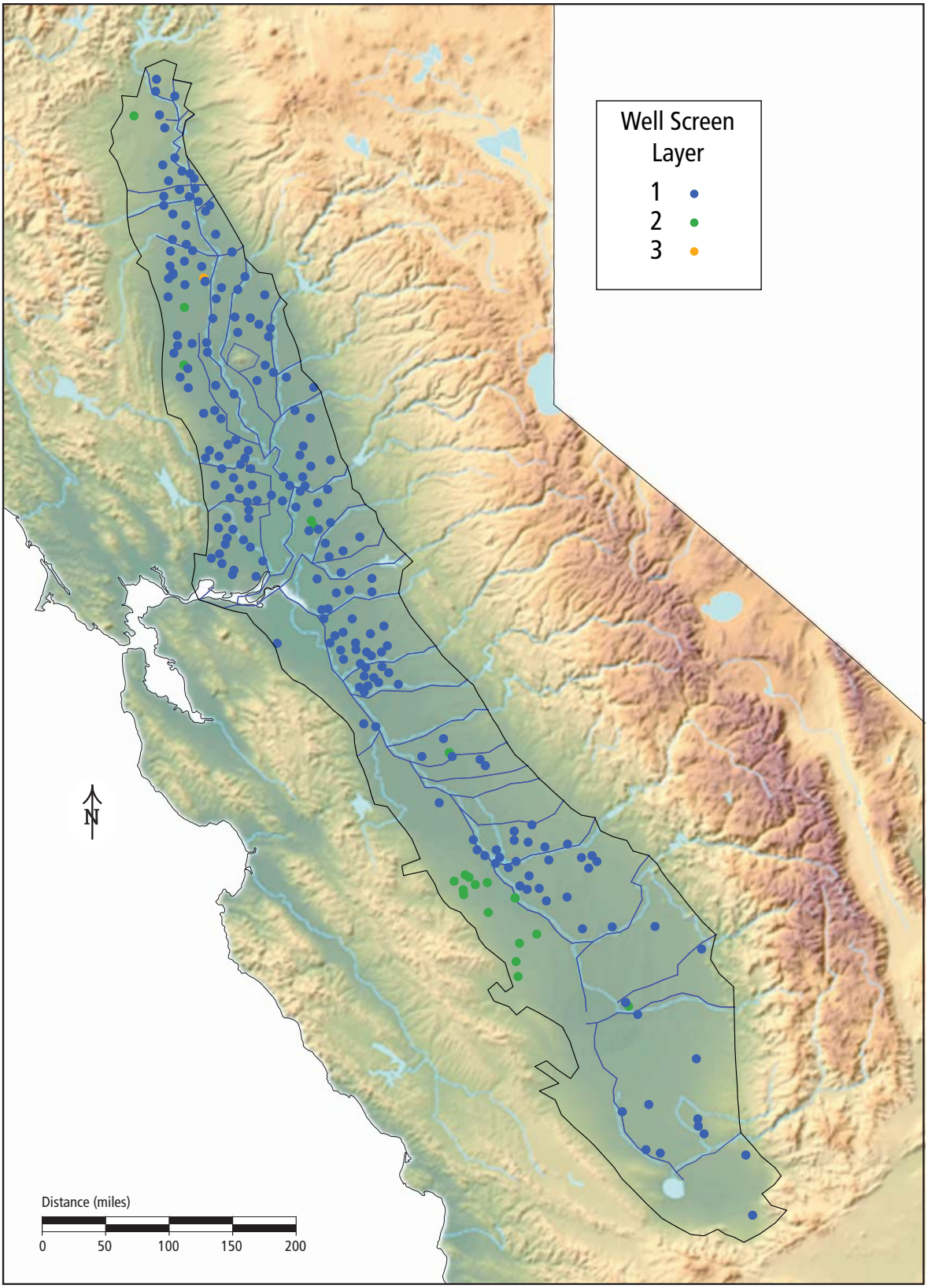


Figure 27. Observation wells for vertical head differences used in phase one of C2VSim calibration.

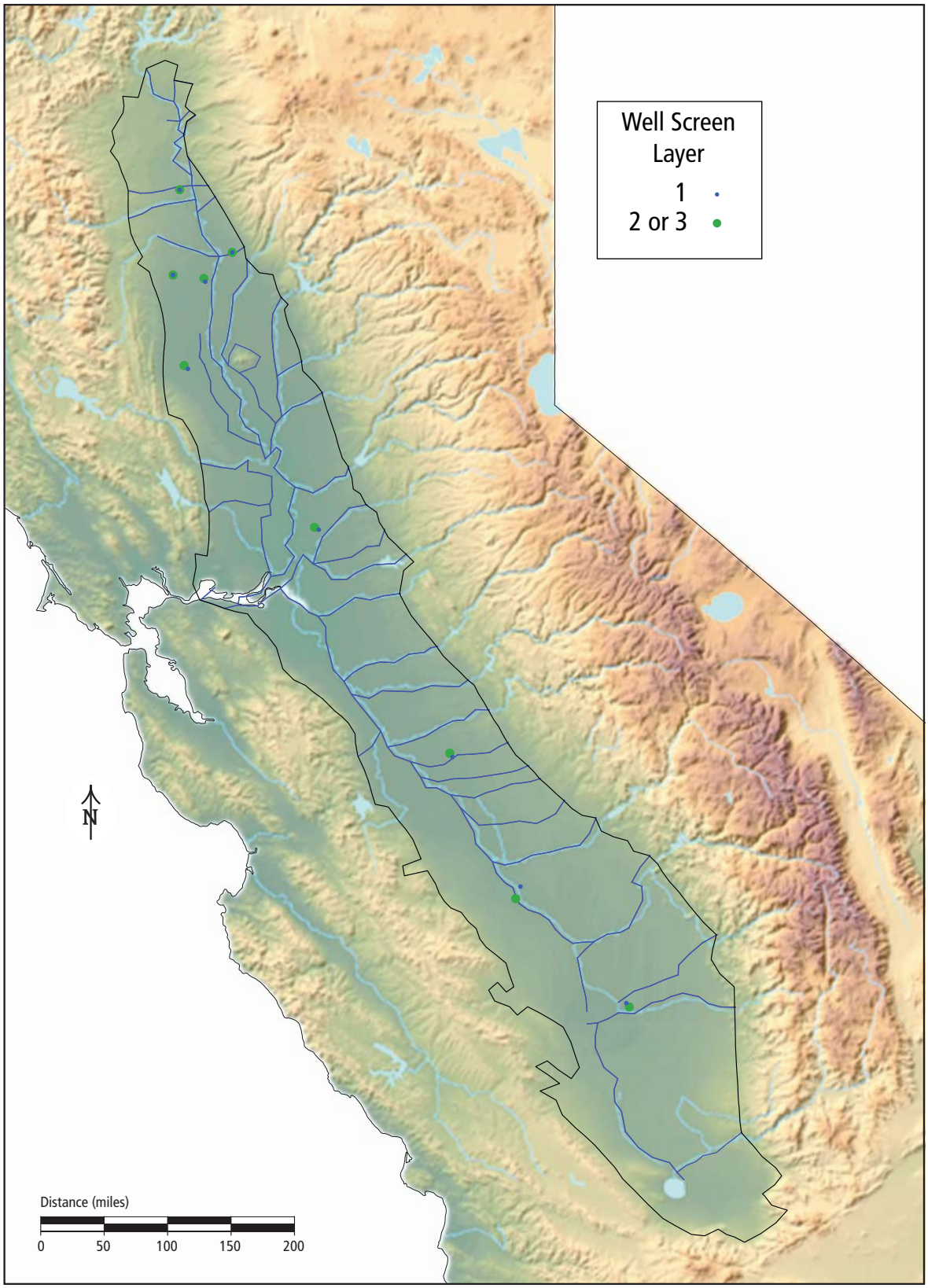
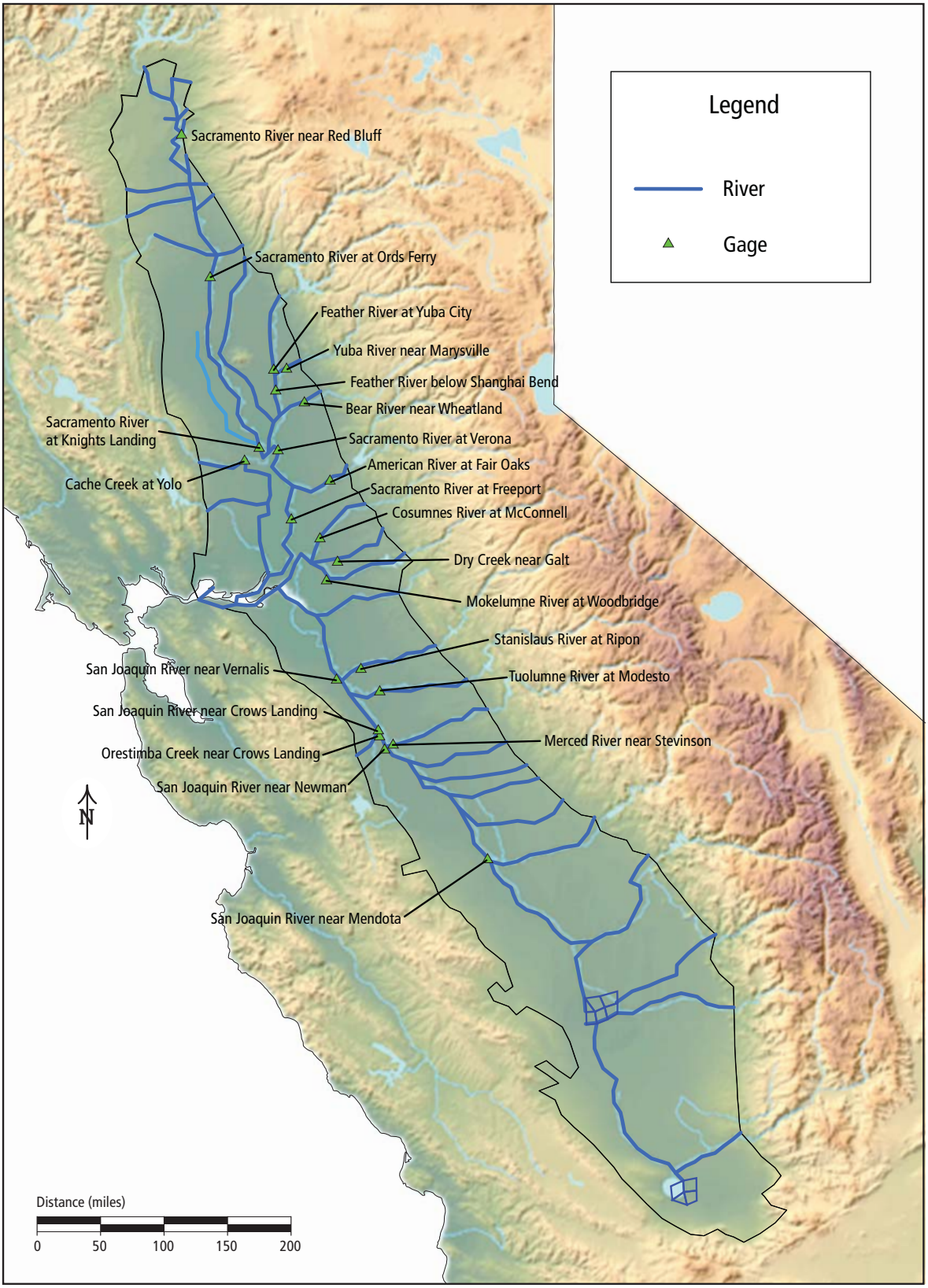


Figure 28. Surface water flow gages used in C2VSim calibration.



water flow observations from the earlier calibration phase were retained. These observations were compiled in a PEST-readable format and were used to calibrate parameter values using the local pilot points and at each model node.

The groundwater head and vertical head difference observations identified for the first phase of model calibration were too sparse to support PEST calibration of model parameters at finer scales. An expanded set to groundwater observation wells were selected from a set of more than 17,000 wells in DWR's water-level database. A tool was developed to compare hydrographs for all wells near each model node. This allowed the representative model layer to be identified for wells that lacked screen information but with detailed water level observations. Using this tool, 1,387 wells were selected that (a) were either screened in a single model layer or had water level observations that matched those of a nearby well screened in a single model layer; and (b) had several years of regular water level observations that did not overlap observations from another well near the same model node. For those observation wells with more than one observation per month, one representative observation was selected. From these wells, 121 pairs of wells screened in different layers were used to create vertical head difference observations. This resulted in 56,947 groundwater head and 6,034 vertical head difference observations (Figures 30 and 31).

Monthly surface water discharges were compiled for streams discharging from 18 small-stream watersheds from various sources, and converted to units of acre-feet per month (Figure 32). Monthly surface water flow and small-stream watershed discharge observations were converted to logarithmic values with a large negative value applied to low flows, on the advice of John Doherty (personal communication, May 2009), in order to force the PEST program to give equal consideration to meeting high flows and low flows. Land surface subsidence data for 24 extensometers (C. Faunt, written communication) were used to define 3,700 land surface subsidence observations. Maps of cumulative land surface subsidence (Ireland, 1986) were also used to estimate total land surface subsidence at each interior model node, and thus define an additional 1,129 cumulative subsidence observations (Figure 33).

Calibrated Parameters

Simulation of water movement through the distributed flow processes in IWFM, including the land surface, groundwater and surface water flow systems, involves many hydrologic parameters with unique values at each location. Three types of land surface process parameters, six types of small-stream watershed parameters, and two types of unsaturated aquifer parameters were calibrated. Eight parameter types were calibrated for the saturated portion of the aquifer. Conductance parameters were calibrated for river beds and lake beds. The individual parameters and their calibrated values are discussed below.

Ideally, a numerical model grid would have the same spatial scale as that of the natural heterogeneities in the area being modeled. The parameter values in the numerical model could then be consistent with field data. The scale of the C2VSim

Figure 29. Observed groundwater-surface water flows used in C2VSim calibration.

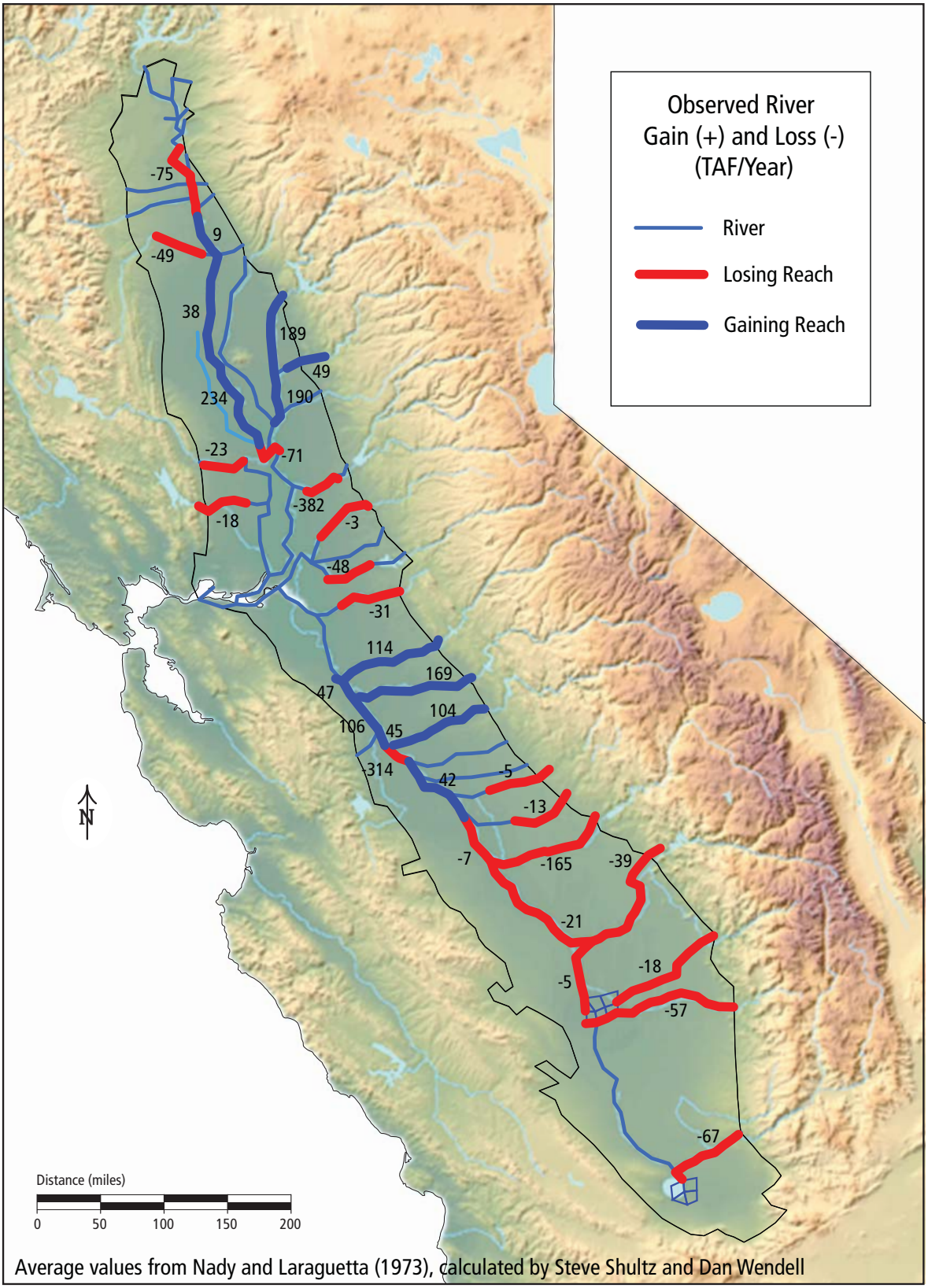


Figure 30. Observation wells for groundwater heads used in phase two of C2VSim calibration.

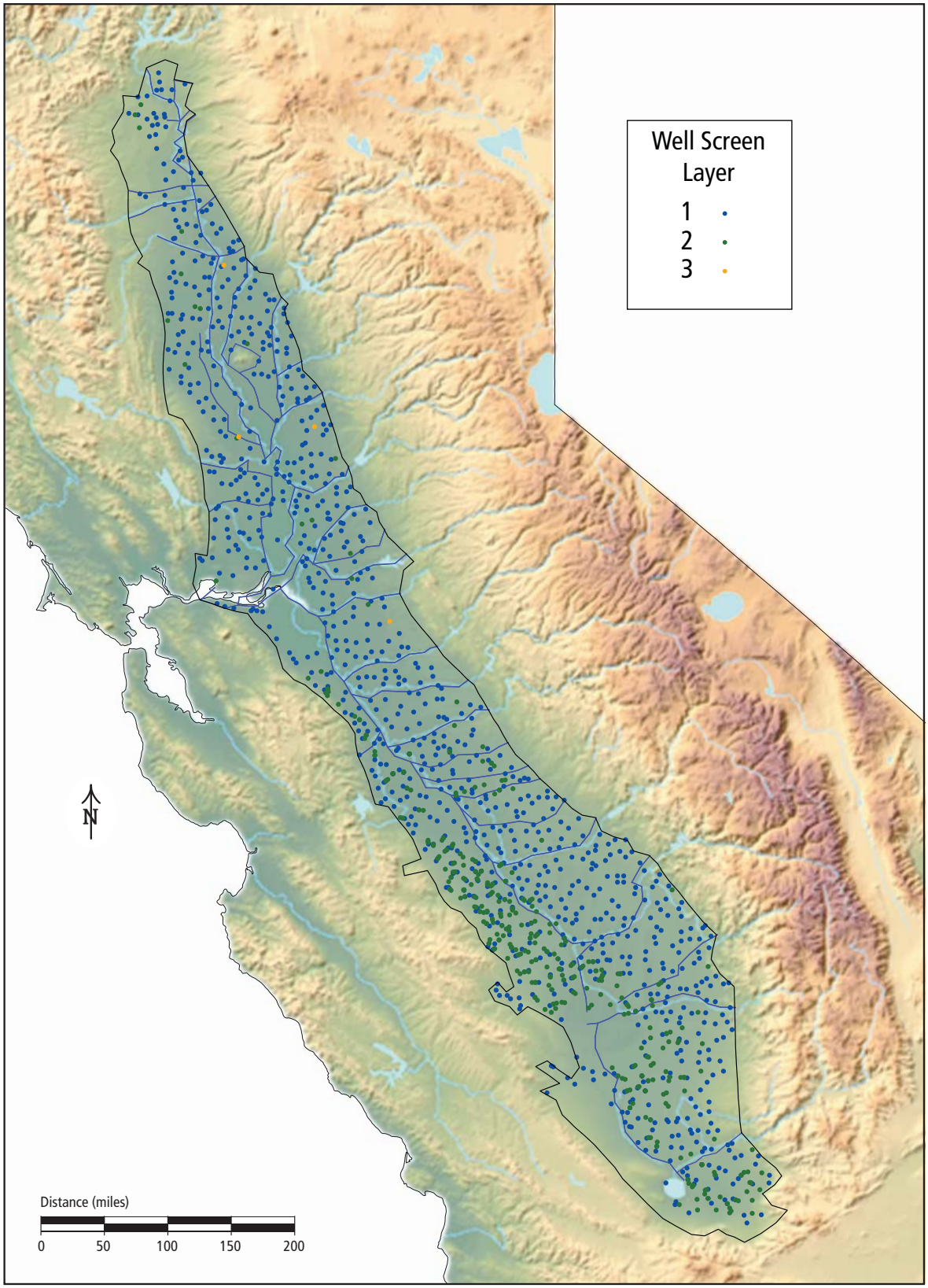


Figure 31. Observation wells for vertical head differences used in phase two of C2VSim calibration.

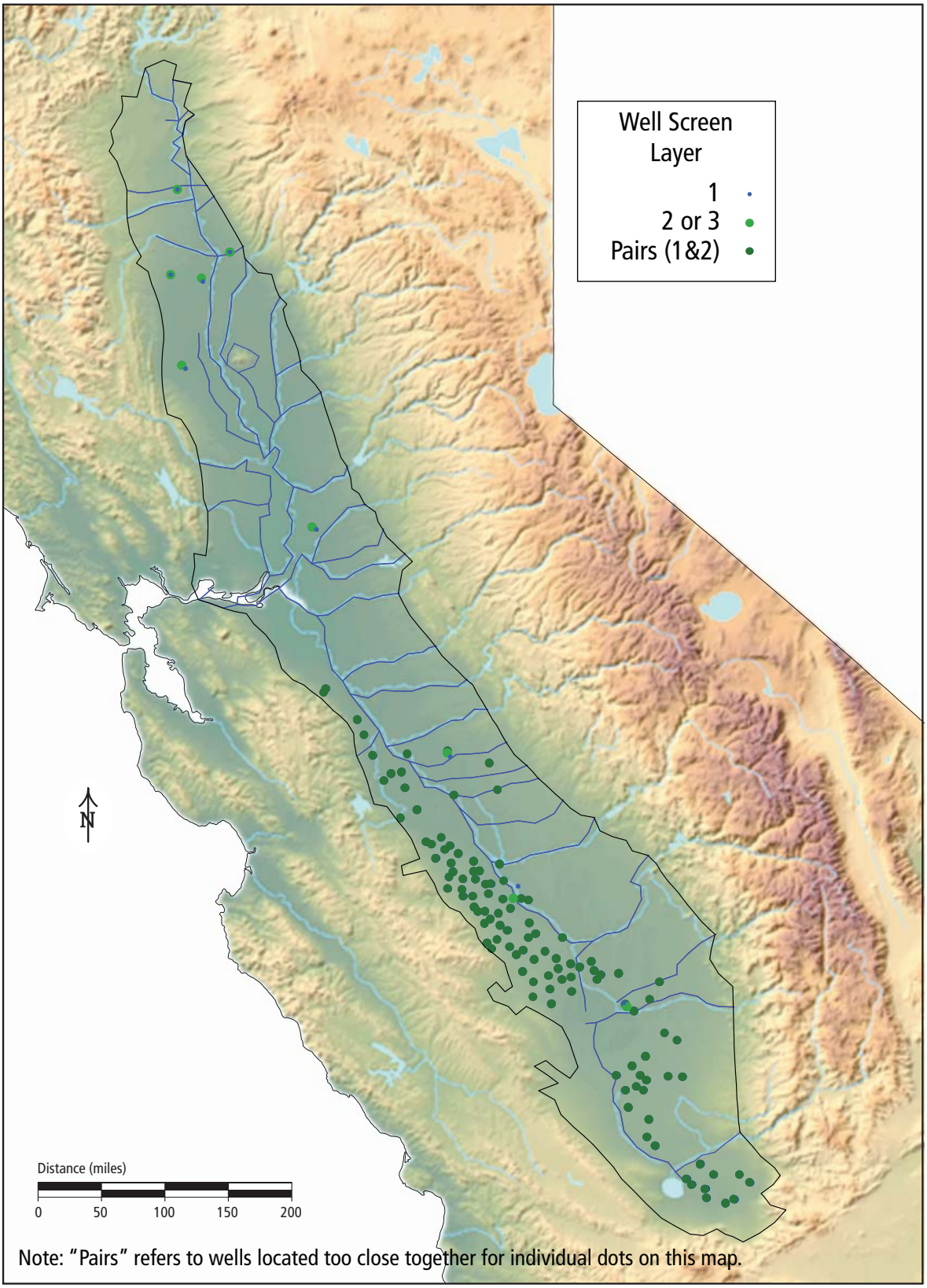


Figure 32. Surface water flow gages for small-stream watersheds used in C2Vsim calibration.

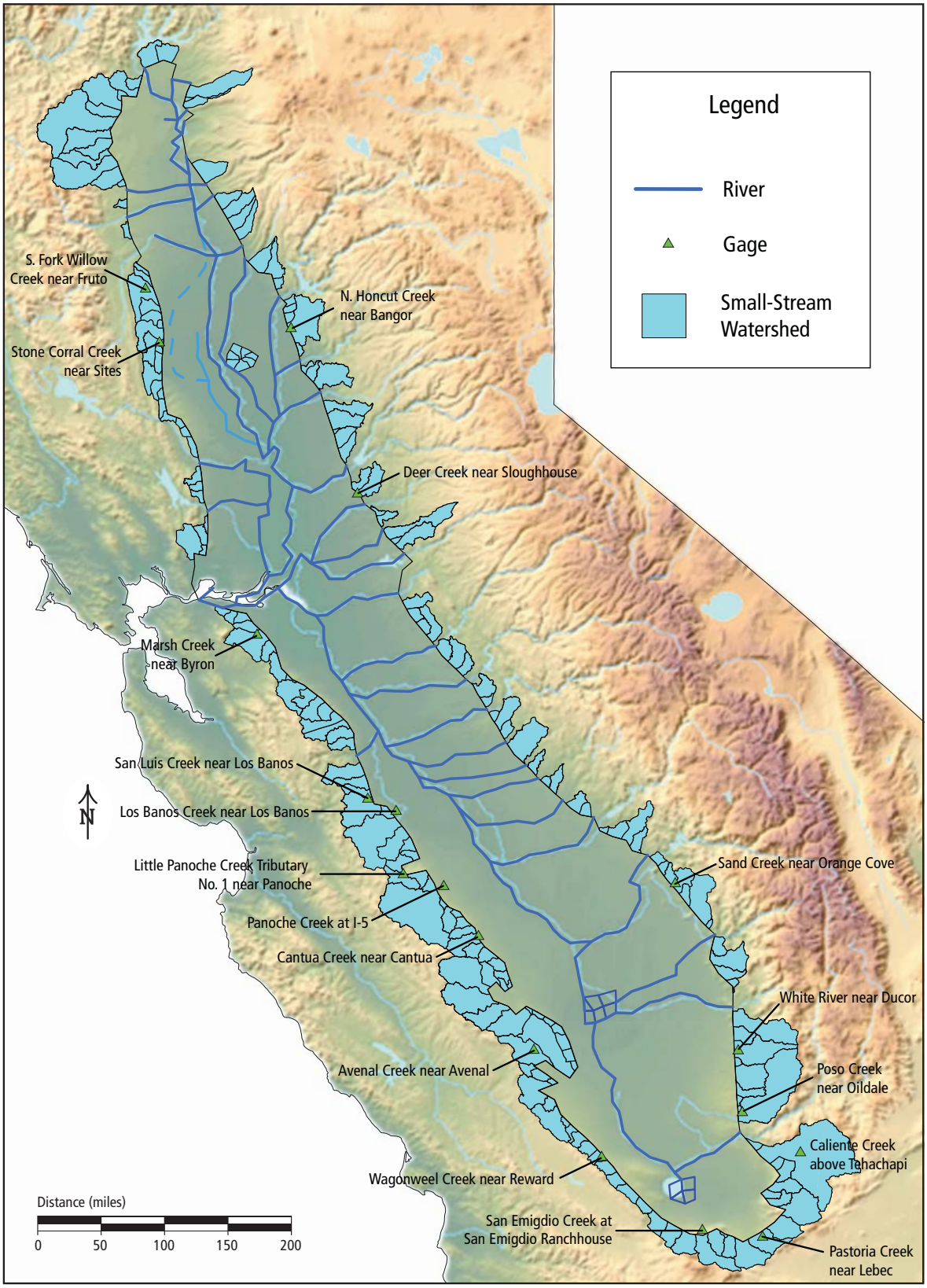
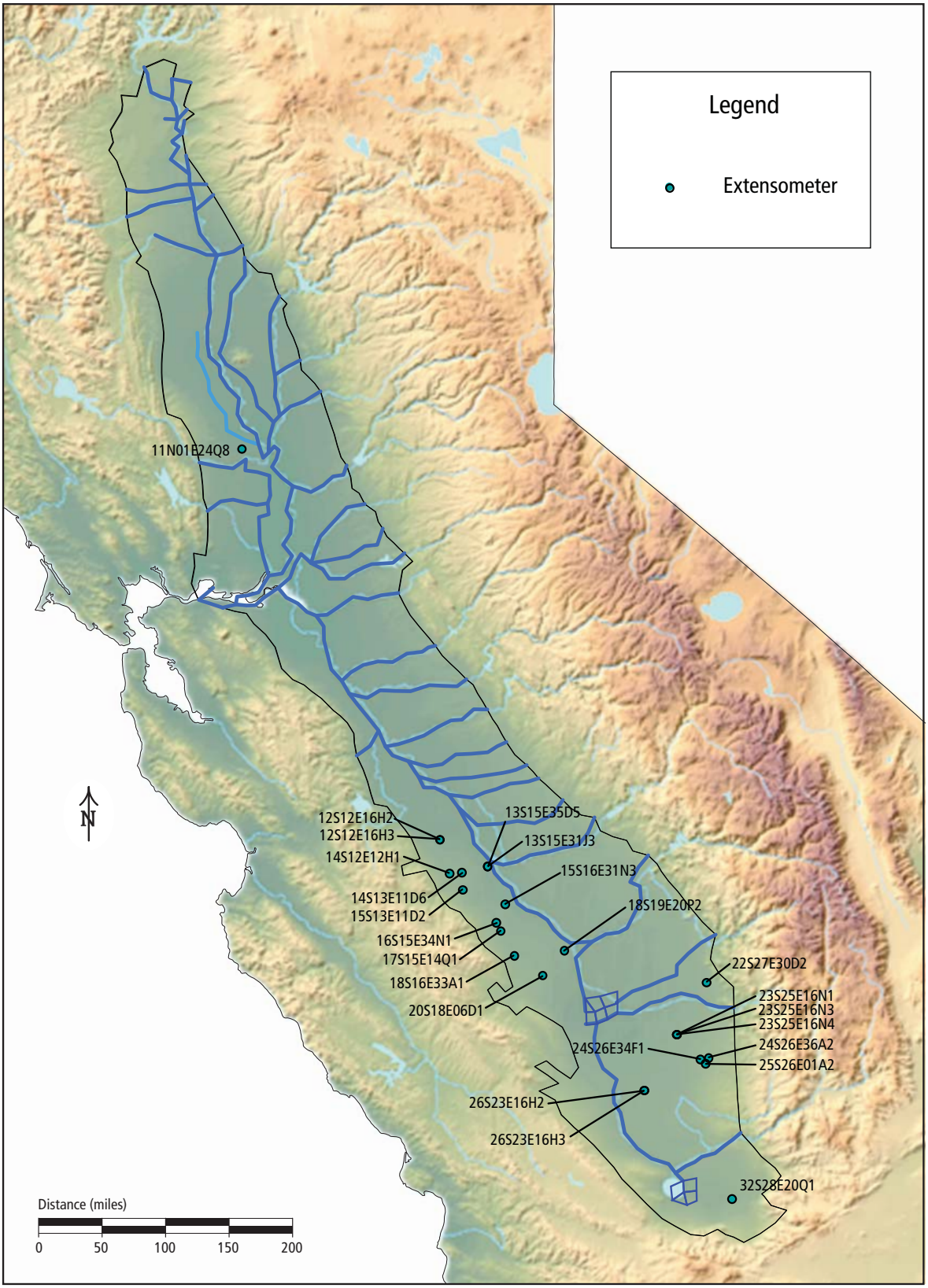


Figure 33. Extensometers with land-surface subsidence observations used in C2VSim calibration.



finite element grid is much larger than the scale of the spatial heterogeneities encountered in the Central Valley. Parameter values calibrated at this coarser scale represent an equivalent homogeneous medium that preserves the mean flux of the heterogeneous deposit, under the range of observed head gradients (Zhang et al. 2010).

IWFM requires curve number, field capacity and effective porosity values for each soil type (A-D) and each land-use class (agricultural, urban, native vegetation and riparian vegetation) in each subregion. Curve numbers describe the partitioning of precipitation into runoff and infiltration. The total porosity, field capacity and vertical hydraulic conductivity of the root zone control the amount of moisture stored in the soil and released as deep percolation. IWFM allows two options in computing the deep percolation: (a) physically-based routing where vertical hydraulic conductivity of the soil is used, and (b) an empirical approach where a fraction of the moisture that is above field capacity becomes the deep percolation (Dogrul, 2012A). In the C2VSim model, the latter approach was used with the deep percolation fraction. Initial values of these parameters, except those for the deep percolation fractions, were obtained from the USDA NRCS SSURGO soil map of the State of California (USDA, 2004A), and then an area-weighted average value for each hydrologic soil group within each subregion was calculated. Curve number values obtained from SSURGO were converted from length units of inches to feet (Dogrul, 2012A). Deep percolation fractions were initially estimated as 80%. The adjusted curve number values and the total porosity, field capacity and deep percolation fraction values served as initial parameter values, and were modified dynamically during model calibration. In each land use class, the curve numbers increased from hydrologic soil group A to hydrologic soil group D, mirroring the reduction in soil infiltration capacity. For the C2VSim subregions, the final values of the adjusted curve numbers ranged from 79 to 97 for the agricultural land use class, 83 to 97 for the urban land use class, and 81 to 97 for the native vegetation land use class. Field capacity ranged from 0.01 to 0.49, effective porosity ranged from 0.26 to 0.50, and deep percolation fraction ranged from 0.011 to 1.00. Curve numbers for the urban land use class were generally greater than for the agricultural and native vegetation land use classes. The values of field capacity and effective porosity did not change during calibration, suggesting the water budget is relatively insensitive to the values of these parameters at the subregion scale. The use of subregional curve numbers for each land use class introduces some unavoidable errors into the rainfall-runoff calculation, but this is expected to be only slightly greater than that introduced by the large scale of the model elements and the errors inherent in estimating runoff rates over such a large area without using a dedicated and complex model (Loague and Freeze, 1985).

Each small-stream watershed requires a single value for the curve number, field capacity, total porosity and vertical soil hydraulic conductivity. Initial values of these parameters were obtained for each small-stream watershed using area-weighted averages from the USDA NRCS SSURGO soil map of the State of California (USDA, 2004A). Curve number values obtained from SSURGO were converted

from length units of inches to feet (Dogrul, 2012A). Each small-stream watershed also requires an average rooting depth, a threshold value for groundwater discharge to streams and recession coefficients for groundwater discharge to streams and to the main aquifer. Initial values of these parameters were taken from the small-streams watersheds of the CVGSM model (James M. Montgomery Consulting Engineers, 1990B). Parameter values were then calibrated for 18 small-stream watersheds for which surface water discharge observations were available. The remaining small-stream watersheds were each grouped with the most geographically similar calibrated watershed, and the parameters of these watersheds were adjusted proportionally to the changes between initial and final values at the calibrated small-stream watersheds. Calibrated field capacities range from 0.006 to 0.35, porosities range from 0.14 to 0.50, rooting depths range from 1.8 to 6.5 ft, vertical hydraulic conductivities range from 0.40 to 14.6 ft/day, and curve numbers range from 59 to 99. The groundwater discharge threshold is very close to 10.0 and the stream recession coefficient equals 0.10 for all small-stream watersheds, and the groundwater recession coefficient ranges from 0.001 to 0.020.

The porosity and hydraulic conductivity of the unsaturated zone control the rate at which deep percolation travels to the saturated portion of the aquifer, and are specified for each model element. Initial values were taken from the CVGSM model (James M. Montgomery Consulting Engineers, 1990B), in which each element has either a porosity value of 0.12 and a conductivity of 1.0 ft/day, or a porosity of 0.08 and a conductivity of 0.25 ft/day. After model calibration, the porosity values ranged from 0.052 to 0.29, and vertical hydraulic conductivity values ranged from 0.25 to 2.0 ft/day.

Several types of parameters describing the physical properties of the saturated portion of the aquifer are specified for each model node and layer. These include horizontal and vertical hydraulic conductivities, specific yield and specific storage, and elastic and inelastic storage coefficients for the three model layers, and the vertical hydraulic conductivity of the Corcoran Clay. Initial values for these parameters were taken from the CVGSM model (James M. Montgomery Consulting Engineers, Inc., 1990B). Final calibrated values for these parameters are discussed below and presented in Table 5.

Table 5. C2VSim model parameter ranges.

Parameter	Model layer	Minimum	Average	Maximum
Horizontal hydraulic conductivity (K_h)	1	5.7	45.9	100.0
	2	7.1	50.2	100.0
	3	2.2	5.1	16.7
Vertical hydraulic conductivity (K_v)	1	0.022	0.100	0.299
	CC	7.3E-5	2.0E-4	2.8E-3
	2	0.022	0.094	0.289
	3	0.005	0.060	0.277
Specific Yield (Sy)	1	0.060	0.192	0.400
Specific storage (Ss)	2	5.1E-6	2.1E-5	7.0E-5
	3	1.6E-6	2.2E-5	5.7E-5
Elastic subsicence coefficient (Sce)	2	5.0E-7	5.9E-6	6.0E-4
	3	5.0E-7	5.8E-6	6.0E-4
Inelastic subsidence coefficient (Sci)	2	1.0E-6	4.7E-4	2.0E-2
	3	1.0E-6	4.7E-4	2.0E-2

Units: Kh and Kv in ft/day, others unitless

CC - Corcoran clay unit of the Tulare Formation

Horizontal and vertical hydraulic conductivities describe the rate at which water flows in response to pressure differences. The calibrated horizontal hydraulic conductivity values for the C2VSim model are shown in Figure 34. The horizontal hydraulic conductivities ranged from 5.7 to 100 ft/day in the top model layer, 7.1 to 100 ft/day in the middle layer, and 2.2 to 16.7 ft/day in the bottom model layer. Vertical hydraulic conductivities, shown in Figure 35, ranged from 0.022 to 0.30 ft/day in the top model layer, 0.022 to 0.29 ft/day in the middle layer, and 0.005 to 0.28 ft/day in the bottom layer. The vertical hydraulic conductivity of the Corcoran Clay, a confining unit on the western side of the San Joaquin River Basin and Tulare Basin, ranged between 7.3 $x10^{-5}$ and 2.8 $x10^{-3}$ ft/day (Figure 36). The horizontal hydraulic conductivity values follow the expected pattern of higher conductivities in the more recent sediments, and lower conductivities in the compacted older sediments. The spatial patterns of hydraulic conductivities also conformed to the geology of the Central Valley, with higher rates in the areas with sediments derived from the Sierra Nevada, and lower rates in areas derived from the Coast Ranges. The calibrated values of the vertical hydraulic conductivity for the model layers show some irregularities around the margins of area occupied by the Corcoran Clay. This is most likely an artifact of the calibration process; there were no observations of vertical flow across only the Corcoran Clay, so the parameter estimation process probably was not sensitive to the vertical conductivities in the model layers above and below the Corcoran Clay.

Figure 34A. C2Vsim horizontal hydraulic conductivity, model layer 1.

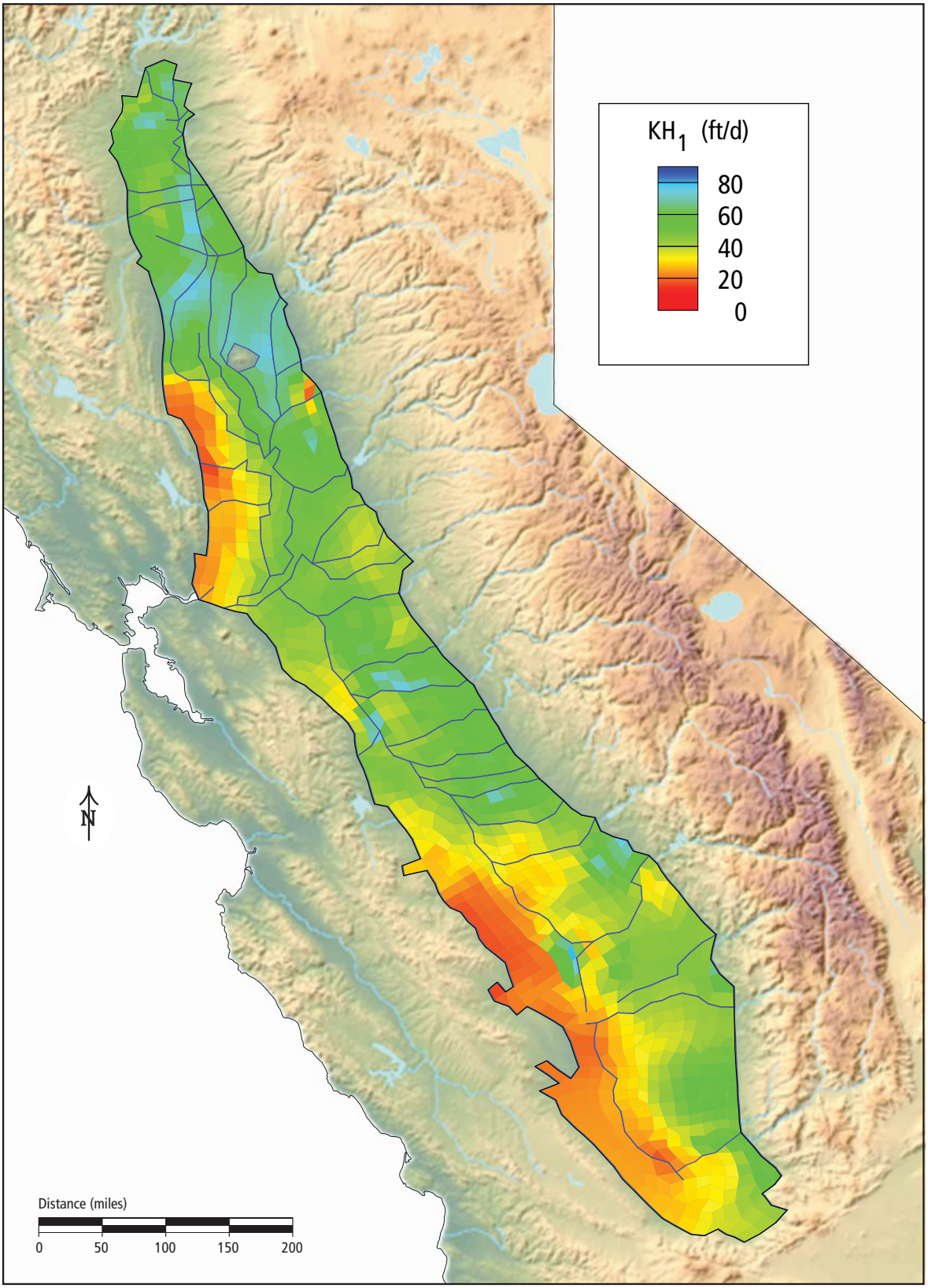


Figure 34B. C2VSim horizontal hydraulic conductivity, model layer 2.

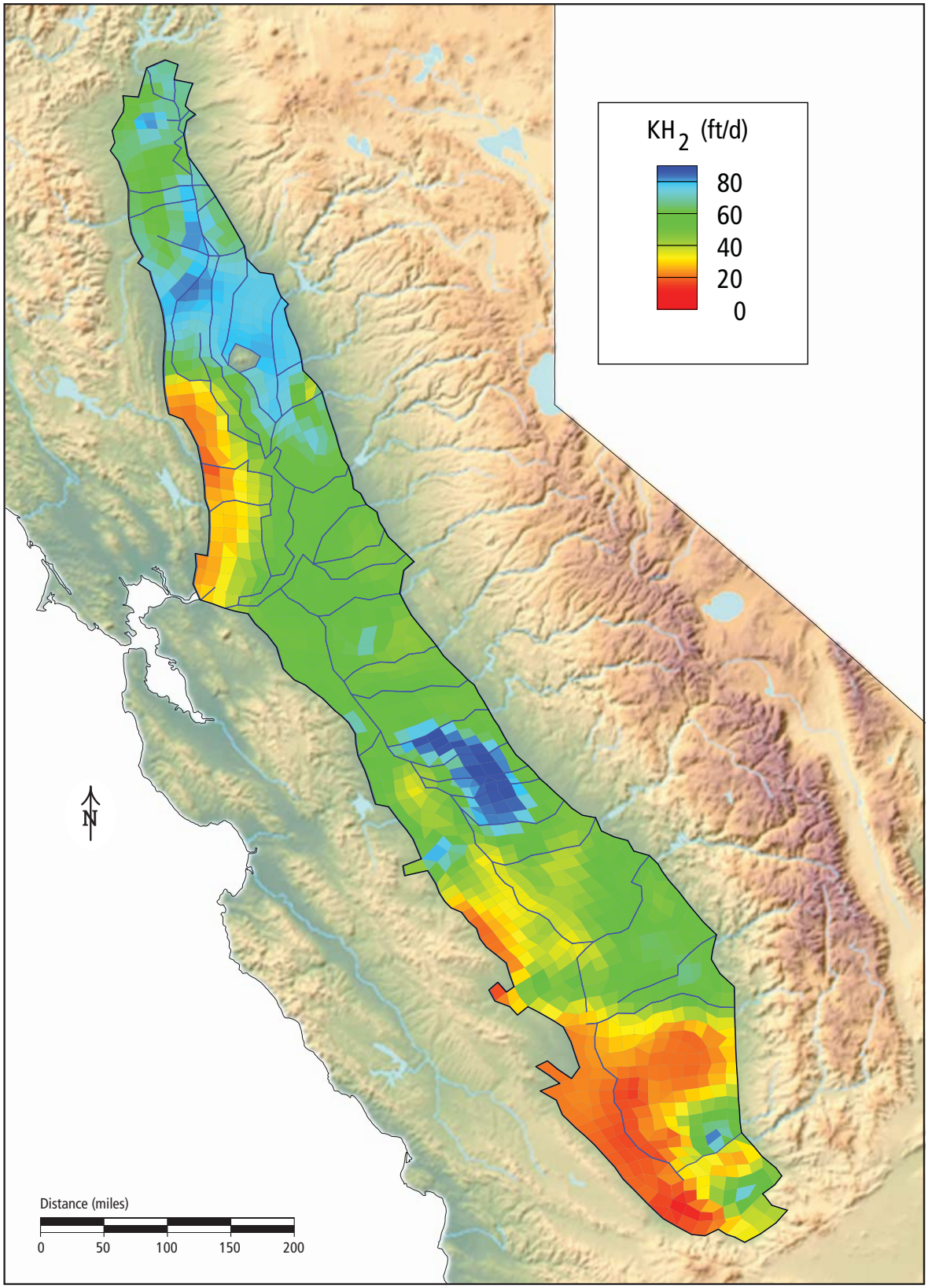


Figure 34C. C2VSim horizontal hydraulic conductivity, model layer 3.

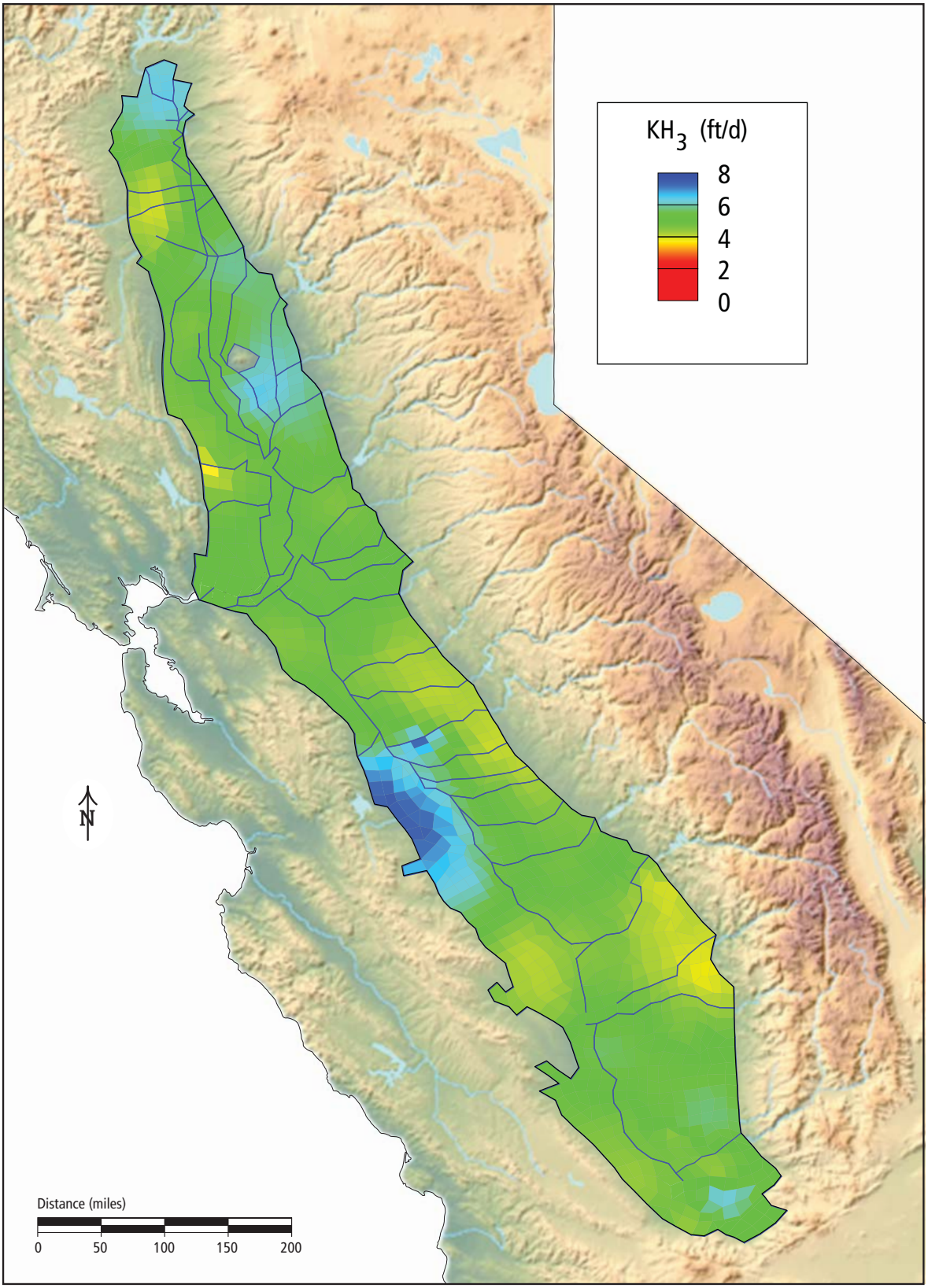


Figure 35A. C2VSim vertical hydraulic conductivity, model layer 1.

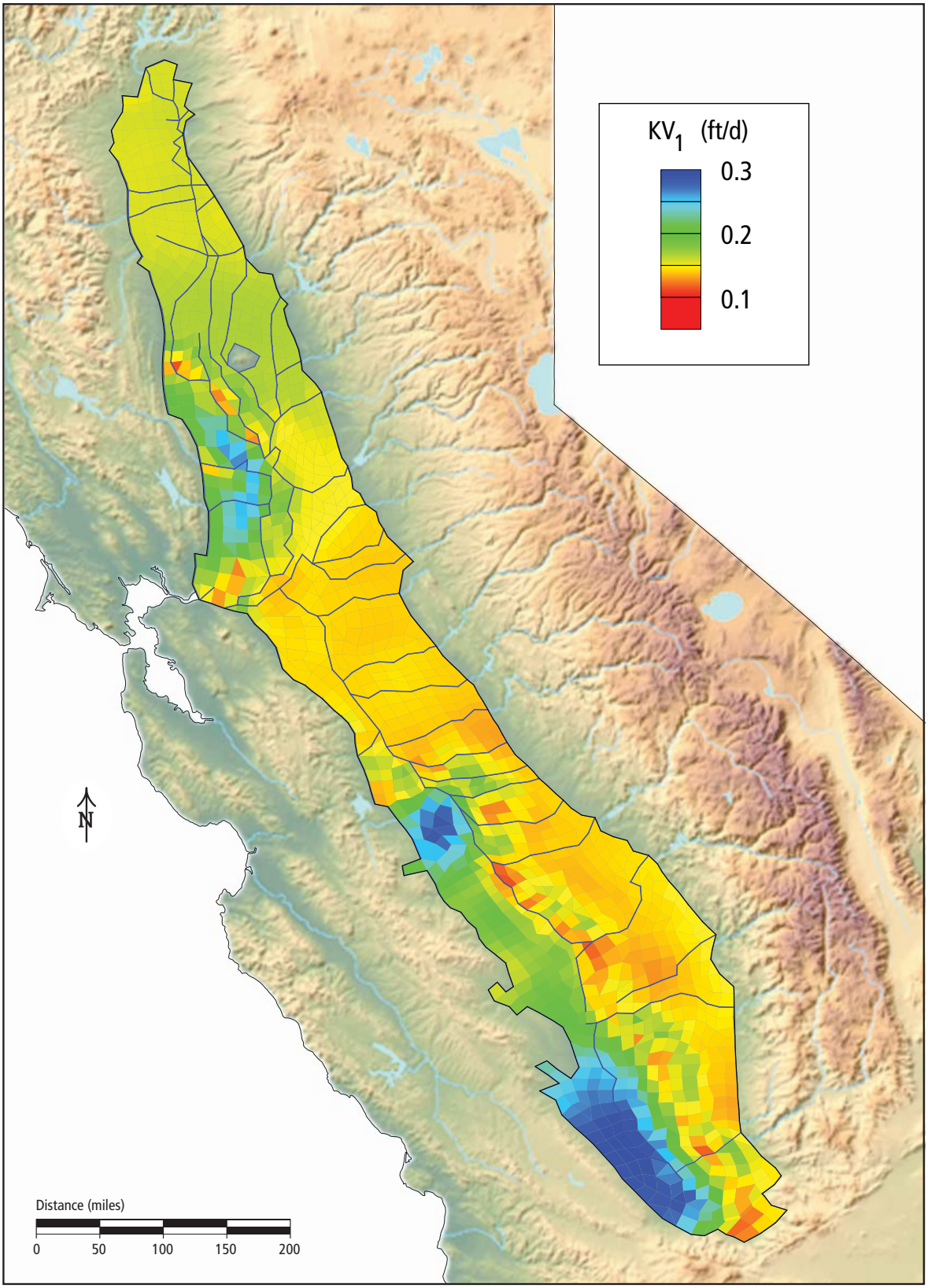


Figure 35B. C2VSim vertical hydraulic conductivity, model layer 2.

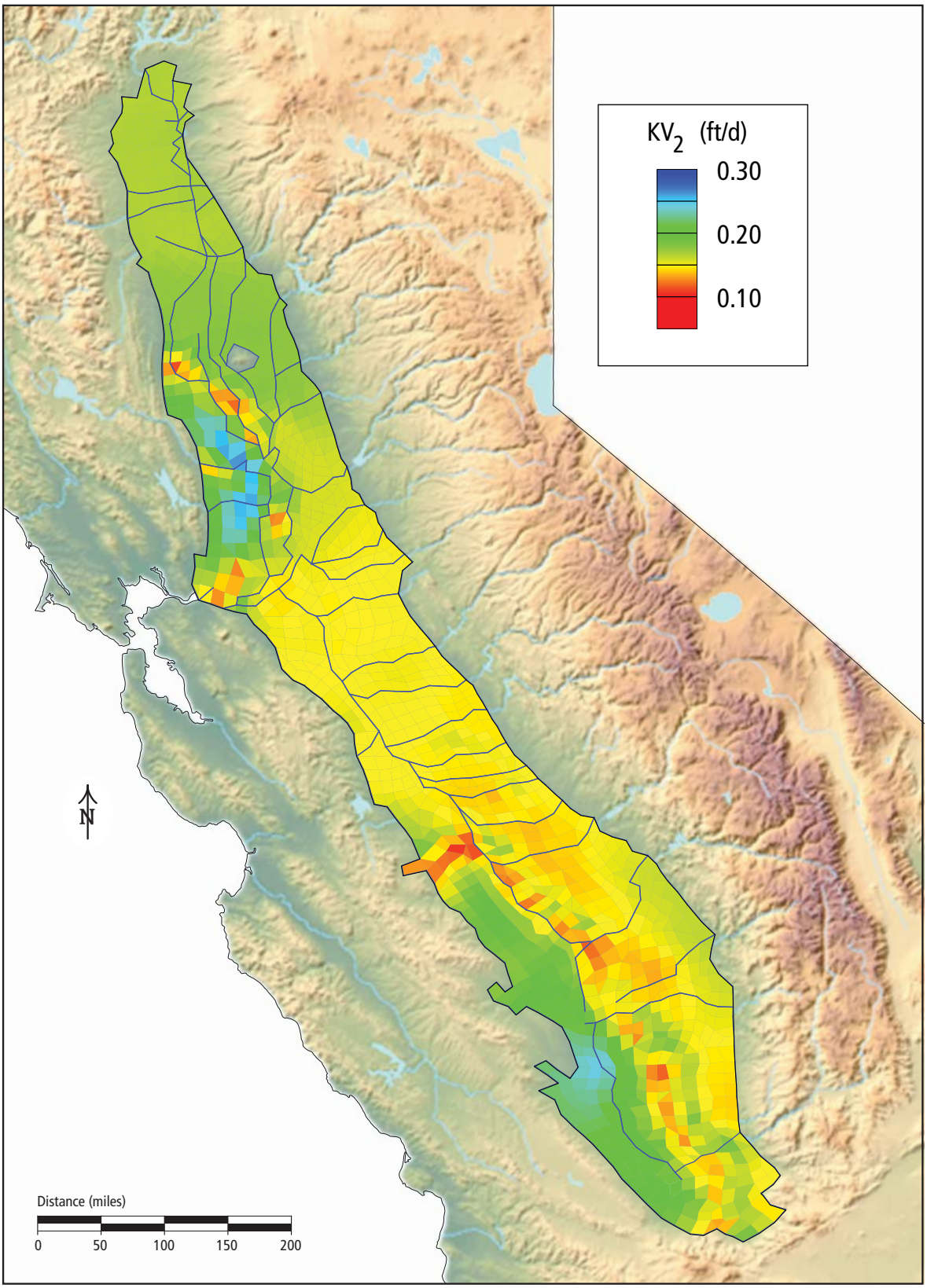


Figure 35C. C2VSim vertical hydraulic conductivity, model layer 3.

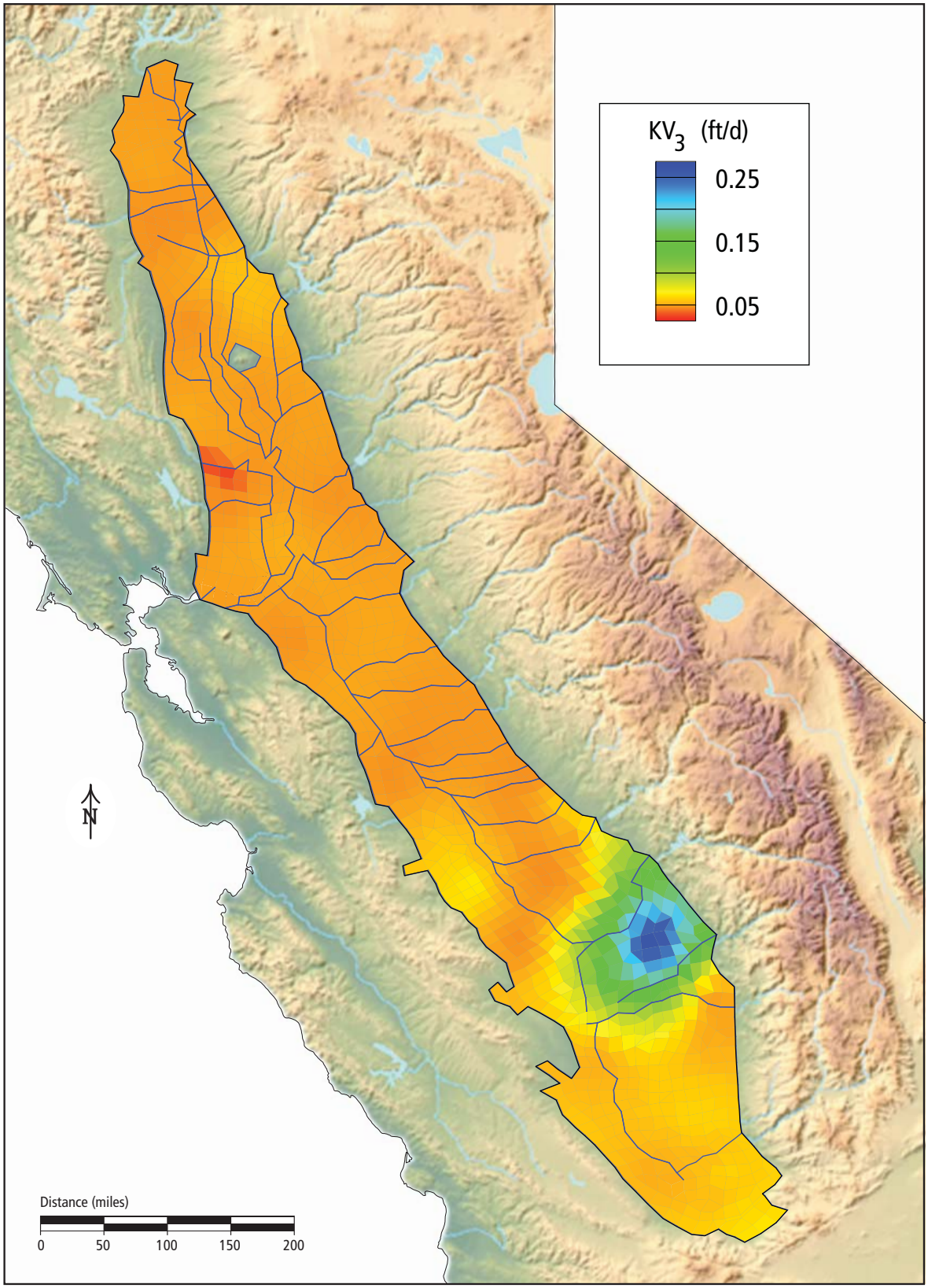
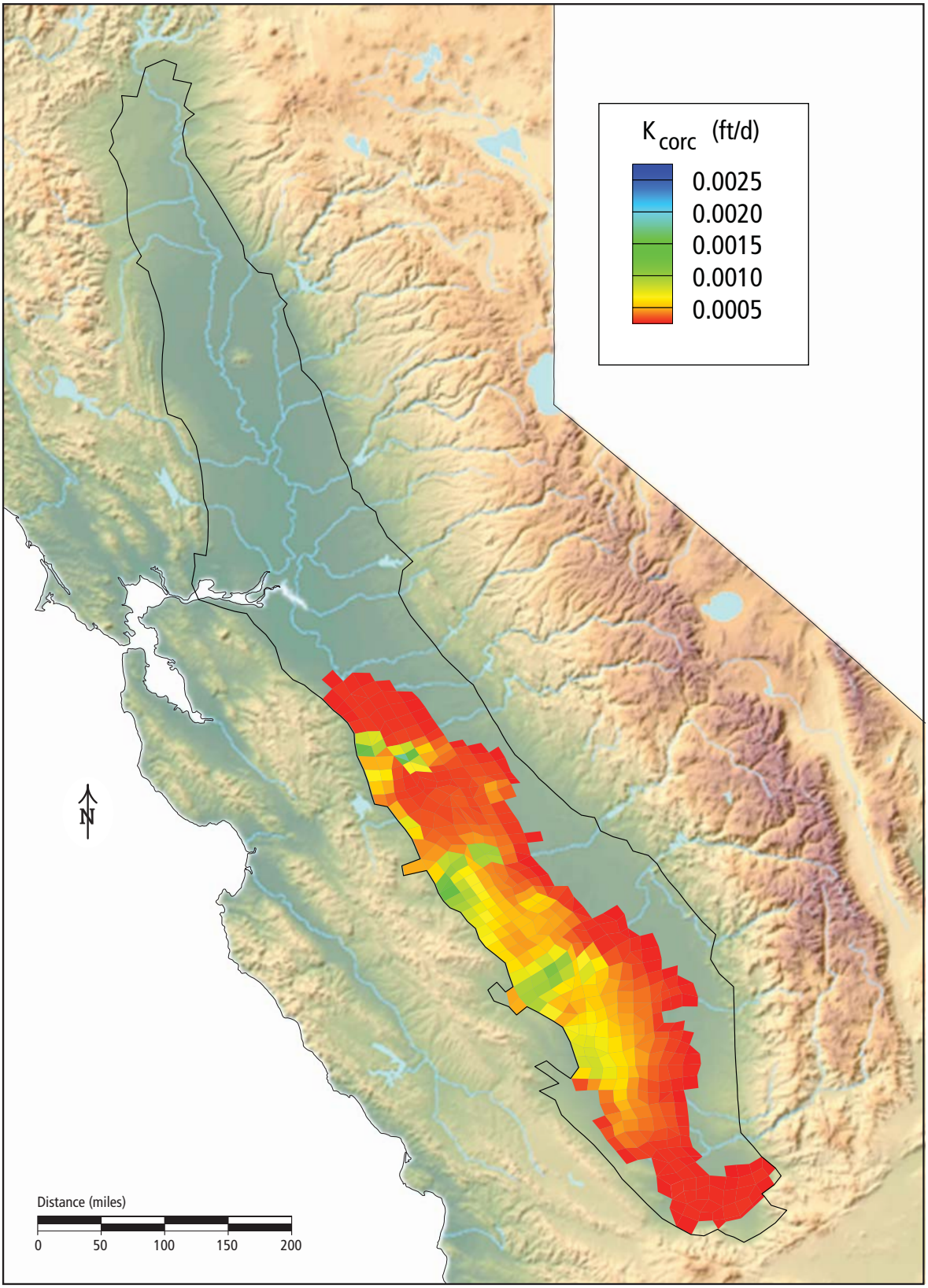


Figure 36. C2VSim vertical hydraulic conductivity, Corcoran Clay.



Specific yields and specific storages describe the rate at which water flows to or from storage in response to changes in the water surface altitude in the unconfined zone or the pressure in the confined zone, respectively (Figure 37). Specific yield values for the top model layer (and the middle layer, if it becomes unconfined) range from 0.06 to 0.40. Specific storage values range from 5.1×10^{-6} to 7.0×10^{-5} in the middle layer and from 1.6×10^{-6} to 5.7×10^{-5} in the bottom layer. Elastic and inelastic storage coefficients describe the rate of aquifer compaction in the confined aquifer layers (and resulting land-surface subsidence) in response to changes in pressure. Elastic storage parameter values range from 5.0×10^{-7} to 6.0×10^{-4} in both the middle and bottom model layers (Figure 38). Inelastic storage parameter values range from 1.0×10^{-6} to 2.0×10^{-2} in both the middle and bottom model layers (Figure 39).

The hydraulic condivities of river beds, specified at each river node, and lake beds, specified for each lake, control the rates at which groundwater and surface water exchanges occur in response to differences between surface water and groundwater levels. River-bed hydraulic conductivities average 1.8 ft/day per foot of channel length and range from 0 to 44 ft/day per foot of channel length (Figure 40). Lake bed conductivities are 0.67 ft/day for all lake elements.

Figure 37A. C2VSim specific yield, model layer 1.

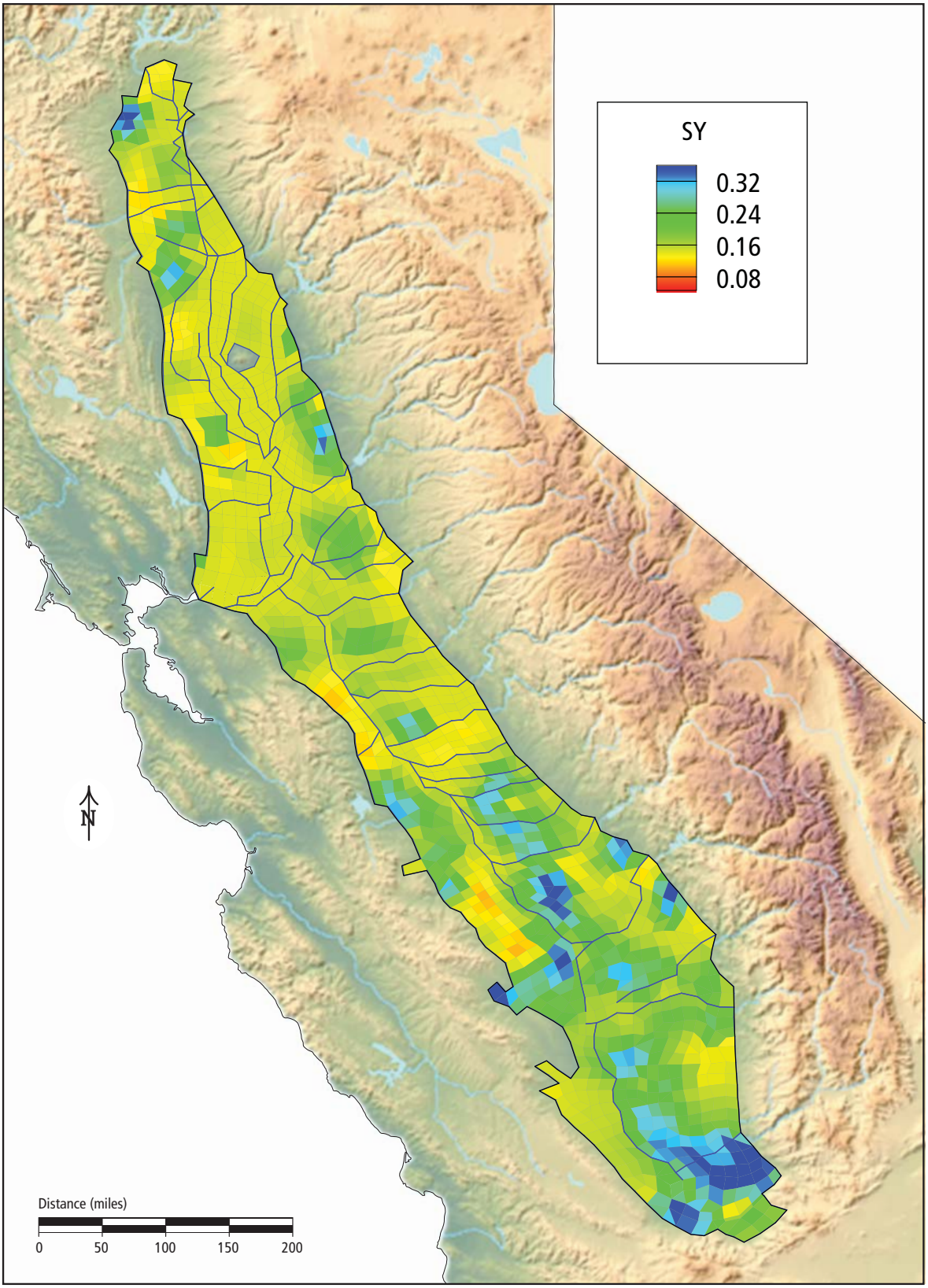


Figure 37B. C2VSim specific storage, model layer 2.

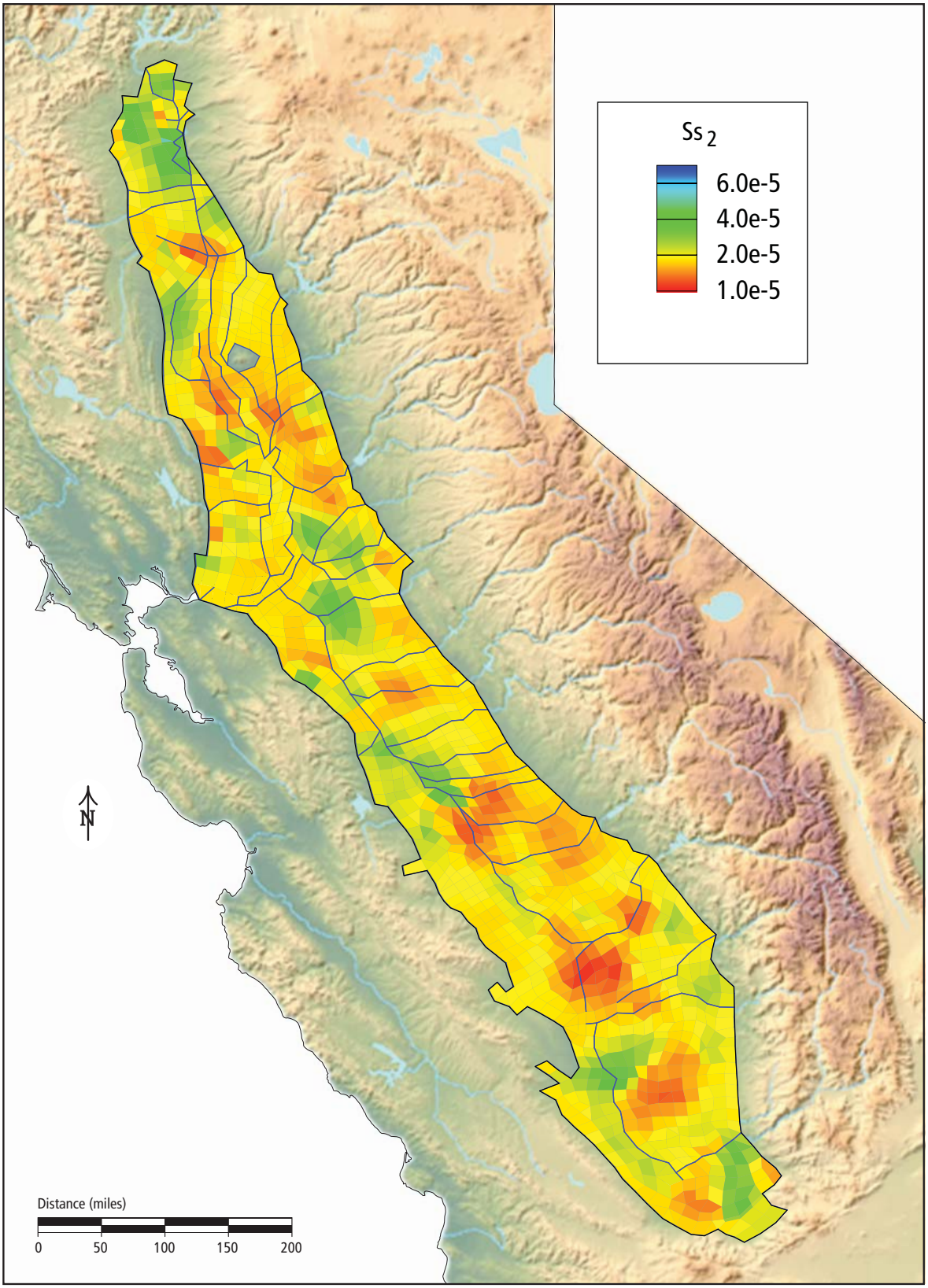


Figure 37C. C2VSim specific storage, model layer 3.

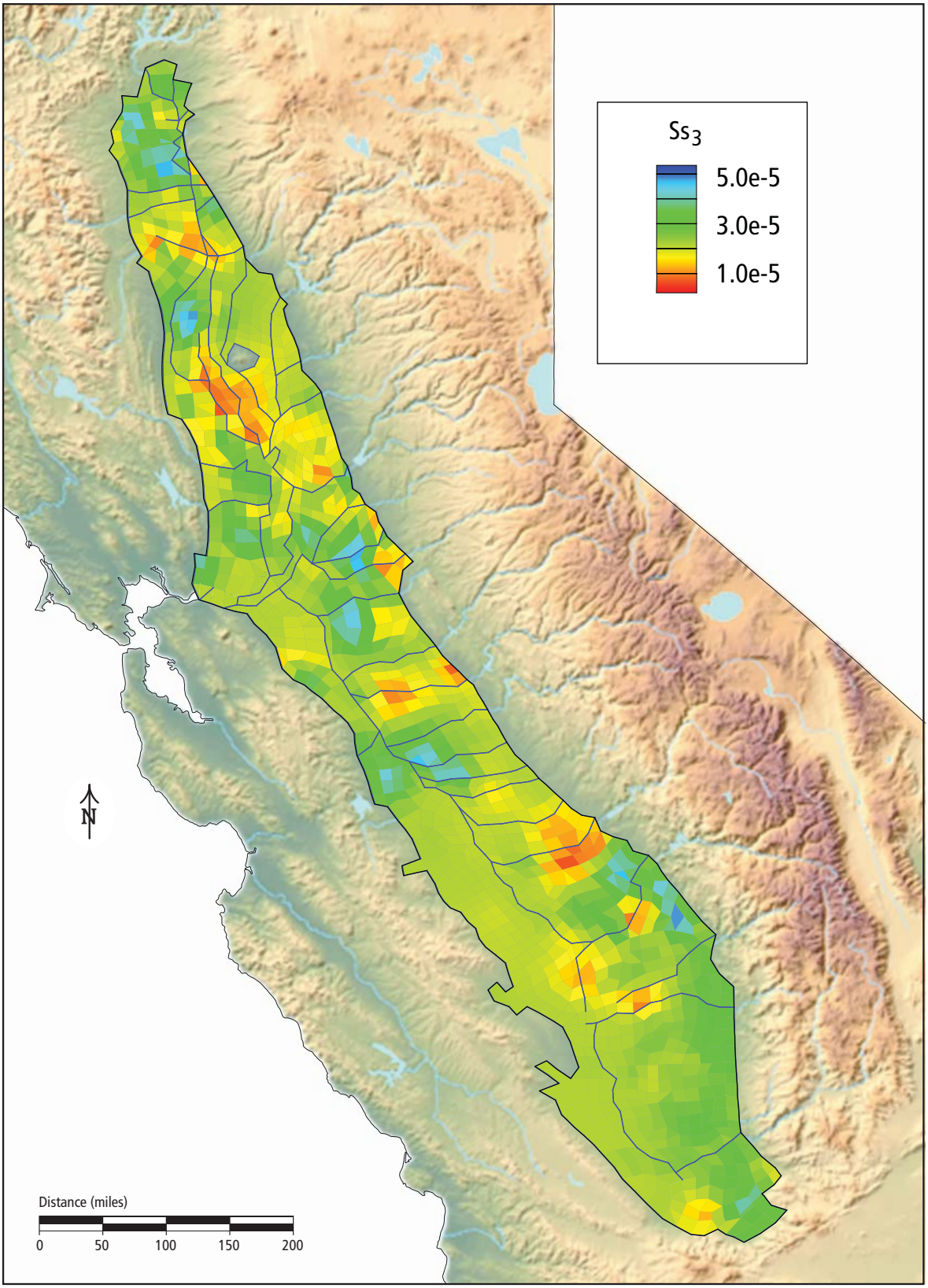


Figure 38A. C2VSim elastic storage coefficient, model layer 2.

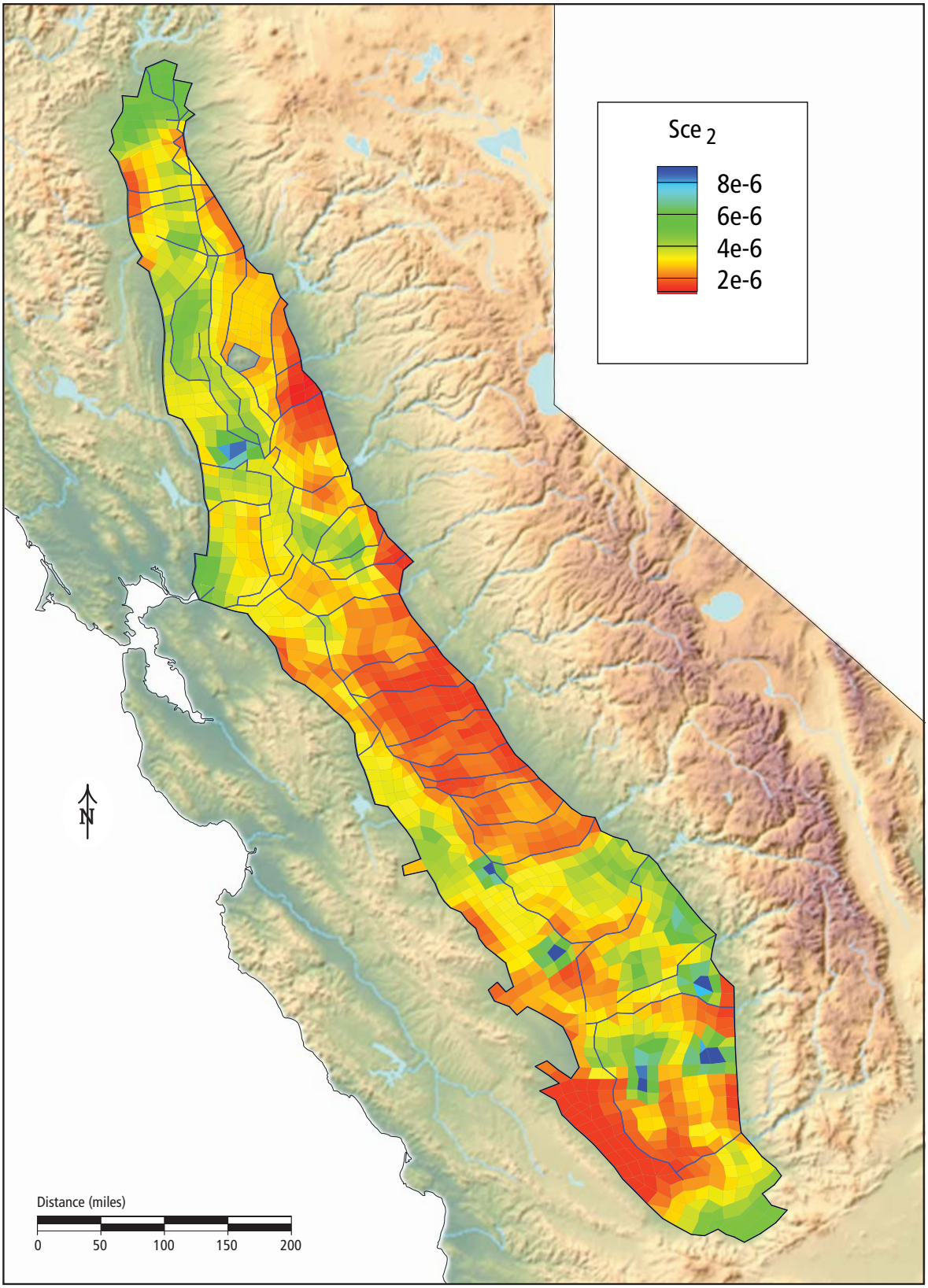


Figure 38B. C2VSim elastic subsidence coefficient, model layer 3.

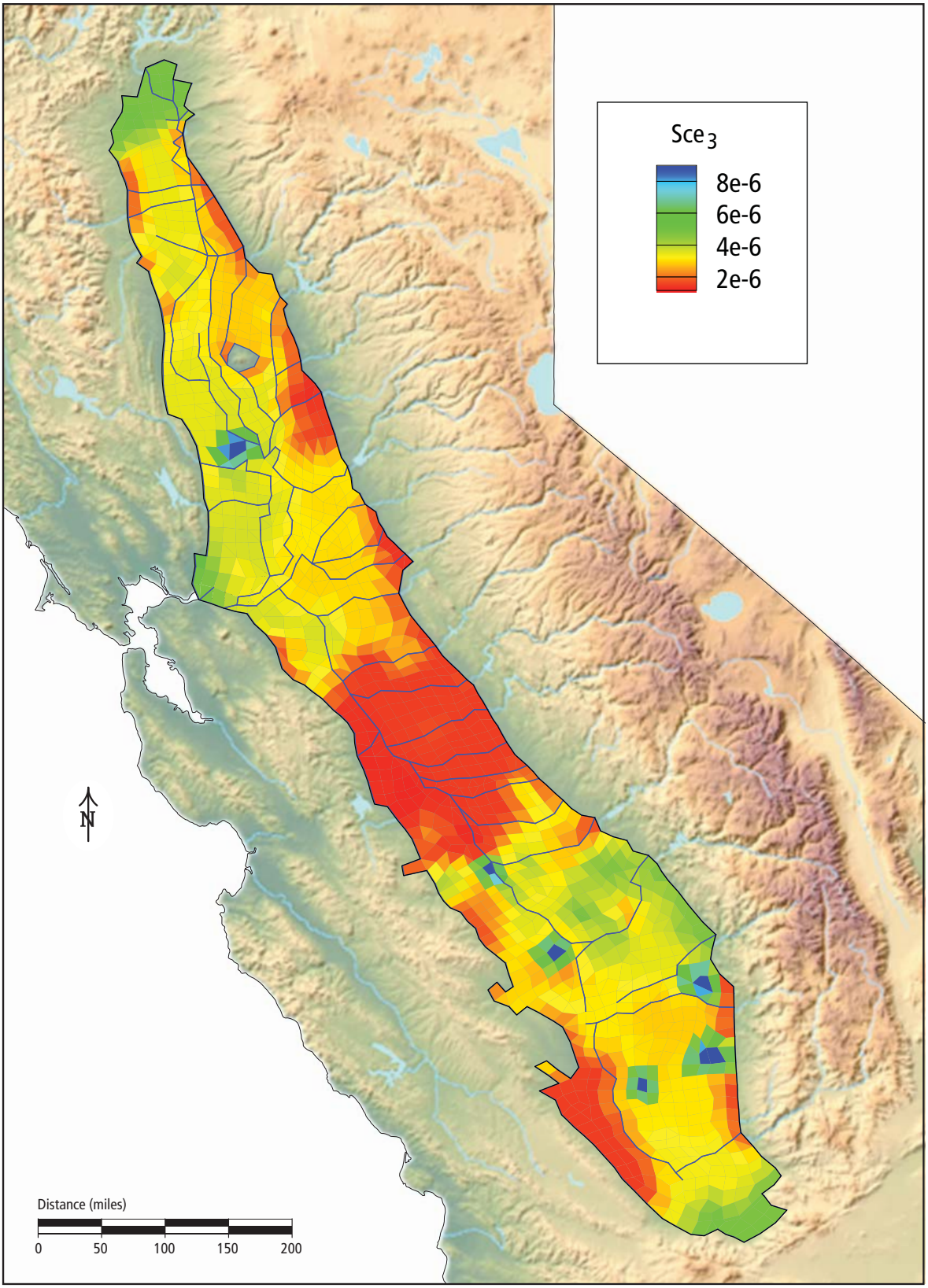


Figure 39A. C2VSim inelastic subsidence coefficient, model layer 2.

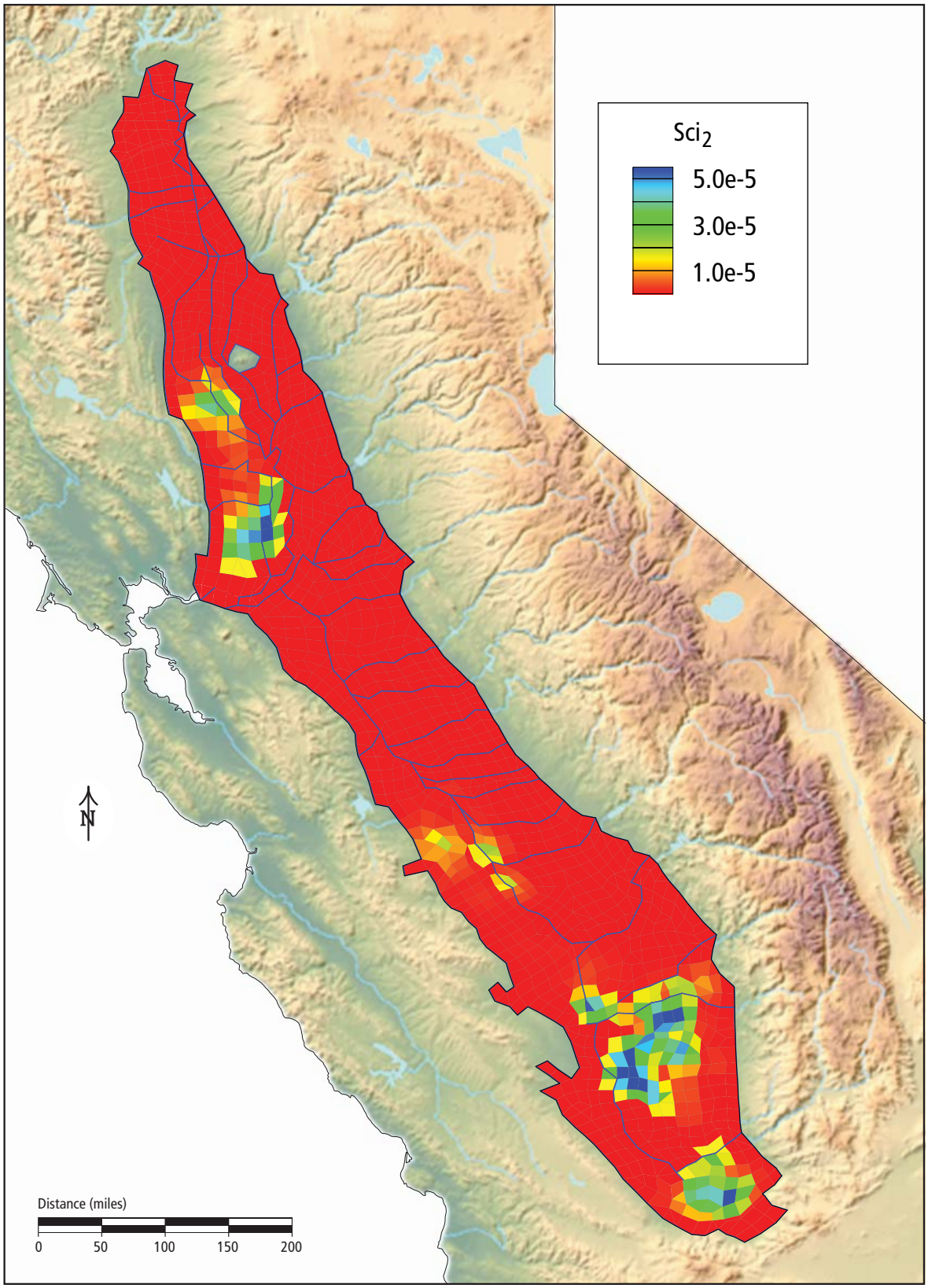


Figure 39B. C2VSim inelastic subsidence coefficient, model layer 3.

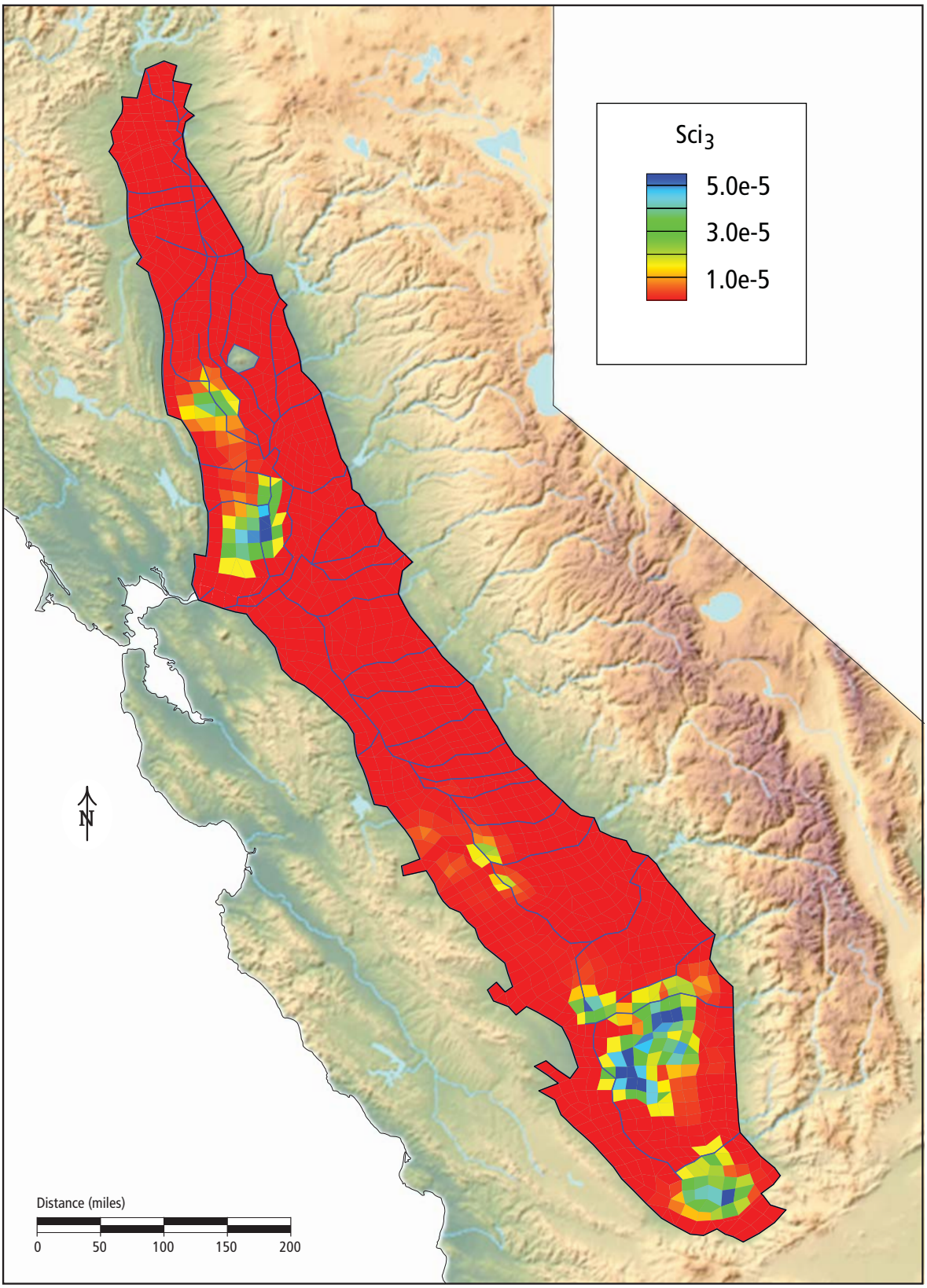
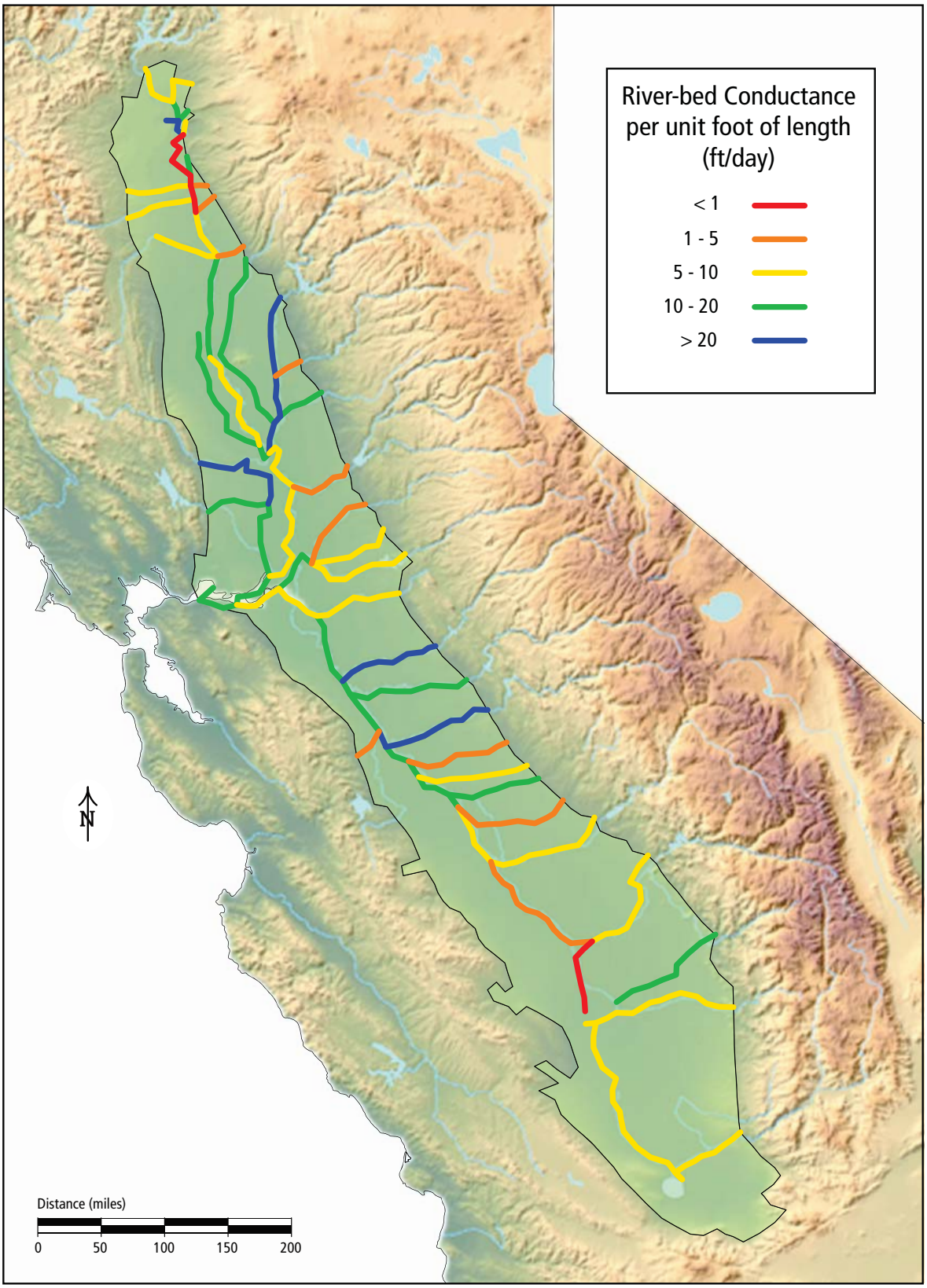


Figure 40. C2Vsim river-bed conductances.



Model Performance

Numerical models are subject to two general types of error (Doherty and Hunt, 2010). First, they present a simplified generalization of the real world, and thus can only simulate spatial and temporal average conditions. Second, the observations used to calibrate the model contain measurement errors. Therefore, a calibrated numerical model can not exactly replicate actual historical conditions, and is generally calibrated to provide an acceptable match to observed conditions.

The quality of the C2VSim model calibration was evaluated by calculating the root mean squared errors and cumulative residuals between simulated and observed values of groundwater head, vertical groundwater head difference, river flow, groundwater-stream interaction flow and land-surface subsidence, and rescaled by dividing the values for each observation type by the respective range. Model performance with respect to the five observation types is summarized in Table 6. The large number and spatial distribution of groundwater head and river flow observations allowed a more detailed analysis of model performance with respect to these observations.

Table 6. C2VSim model performance.

Observation Type	Root Mean Squared Error	Residual	$\frac{\text{RMSE}}{\text{Range}}$	$\frac{\text{Residual}}{\text{Range}}$
Groundwater heads	51.6	-0.06	0.041	-0.000
Vertical Groundwater Head Difference	85.6	-0.4	0.12	-0.001
River Flows	145,591	-13,720	0.0	-0.00
River-Groundwater Flows	11,902	6,093	0.31	0.16
Subsidence	17.37	-11.5	2.8	-1.9

Units: heads are in feet, flows in acre-feet per month

The calibration data set included 62,981 groundwater head observations at 1,378 locations. Model performance in relation to the groundwater head observations is summarized in Table 7. The root mean square error for groundwater heads is 51.6 ft for the model and the rescaled root mean squared error is 0.041. The cumulative residual is -0.1 ft and the rescaled cumulative residual is -0.0002. Figure 41 shows that the simulated heads are generally close to the observed heads in most model subregions, with clear patterns to these differences for only a few wells. Some simulated values are very different from the observed values in model subregions 14, 19, 20 and 21, which exhibit the highest root mean squared and cumulative residual values. This is most likely due to differences between actual water demands and those simulated by the C2VSim model, which would result in groundwater pumping rates that are significantly higher or lower than actual rates. Some observation wells may also be located too close to wells that are actively pumping.

Figure 41. Simulated and observed groundwater heads for the calibrated C2VSim model, 1975-2003.

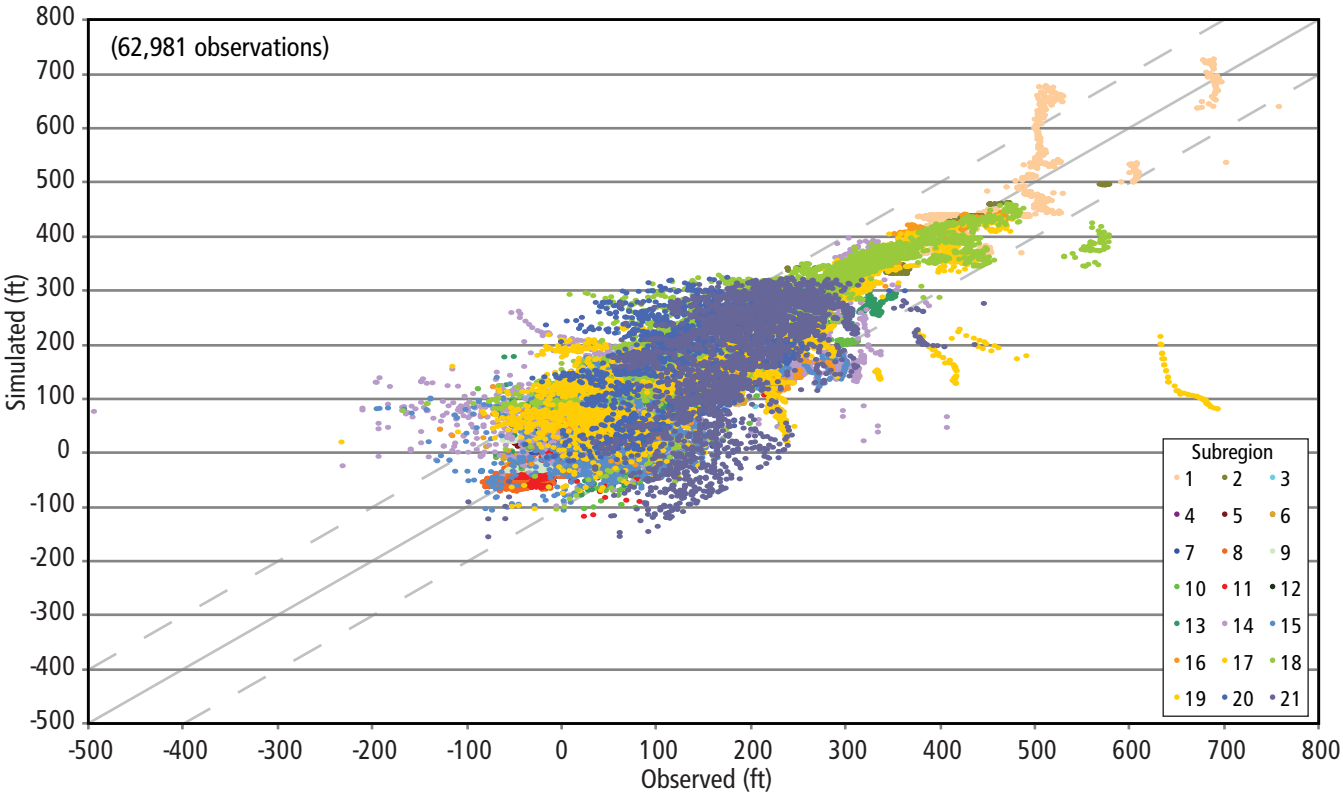


Table 7. C2VSim model performance: Water level observations.

Subregion	DSA	Wells	WL Obs	RMSE	Residual	RMSE / Range	Residual / Range
Sacramento Valley							
1	58	24	1,654	42.1	5.8	0.109	0.015
2	10	45	3,665	25.0	4.6	0.052	0.009
3	12	54	4,761	19.1	-3.5	0.078	-0.014
4	15	17	1,087	8.4	4.1	0.062	0.030
5	69	61	4,867	17.7	5.1	0.081	0.024
6	65	53	4,013	26.8	1.9	0.079	0.006
7	70	31	1,545	22.0	1.9	0.087	0.007
	totals	285	21,592	23.8	2.3	0.028	0.003
Eastside Streams							
8	59	62	4,209	16.0	-0.6	0.058	-0.002
Delta							
9	55	42	1,522	19.8	7.0	0.135	0.048
San Joaquin Basin							
10	49A	101	3,567	37.8	8.2	0.094	0.021
11	49B	37	2,163	22.3	10.6	0.085	0.040
12	49C	24	835	25.7	-13.0	0.111	-0.056
13	49D	144	5,484	36.3	-14.3	0.082	-0.032
	totals	306	12,049	34.0	-3.1	0.077	-0.007
Tulare Basin							
14	60A	164	3,416	87.0	20.3	0.096	0.022
15	60B	135	4,467	59.0	11.8	0.119	0.024
16	60C	40	1,613	36.0	6.2	0.059	0.010
17	60D	43	1,793	42.4	14.5	0.060	0.021
18	60E	107	4,817	64.2	-34.7	0.086	-0.047
19	60F	69	2,680	109.4	5.4	0.141	0.007
20	60G	39	1,517	87.9	-50.0	0.219	-0.125
21	60H	86	3,306	94.1	13.6	0.153	0.022
	totals	683	23,609	76.9	-1.1	0.065	-0.001
	ALL	1378	62,981	51.6	-0.1	0.041	-0.0002

RMSE = Root mean squared error

Units for RMSE, residual and range are ft

The calibration data set also included 4,750 monthly river flow observations at 22 locations. Model performance in relation to these observations is summarized in Table 8. The rescaled root mean squared error for river flows of 0.022 and the rescaled cumulative residual of -0.002 indicate the model is very good at replicating observed flow values. The Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) is 0.7 or greater for 19 of the 22 locations, indicating the simulated flows closely match the observed values. The low Nash-Sutcliffe efficiency of -9.57 at San Joaquin River near Mendota indicates the model does not accurately simulate flows in this reach. This is most likely due to surface water import and/or diversion operations that are not included in the model.

Figure 42 shows that simulated flows are generally close to observed flows at low and moderate values, and diverge for extremely high flow values. The C2VSim river network was compiled to represent dry-season hydrology, and thus there may be large differences between simulated and observed flow values for extremely high stream flows.

The rescaled root mean square error and residual of the individual flow gauges show that the model performs well at all gauges with the exception of several gauges on major rivers. The simulated flows at these gauges include accumulated differences from upstream areas, and the difference between simulated and observed flows suggests that there are additional diversions from and/or return flows to the reaches upstream from these gauges that are not simulated.

Figure 42. Simulated and observed surface water flows for the calibrated C2VSim model, 1975-2003.

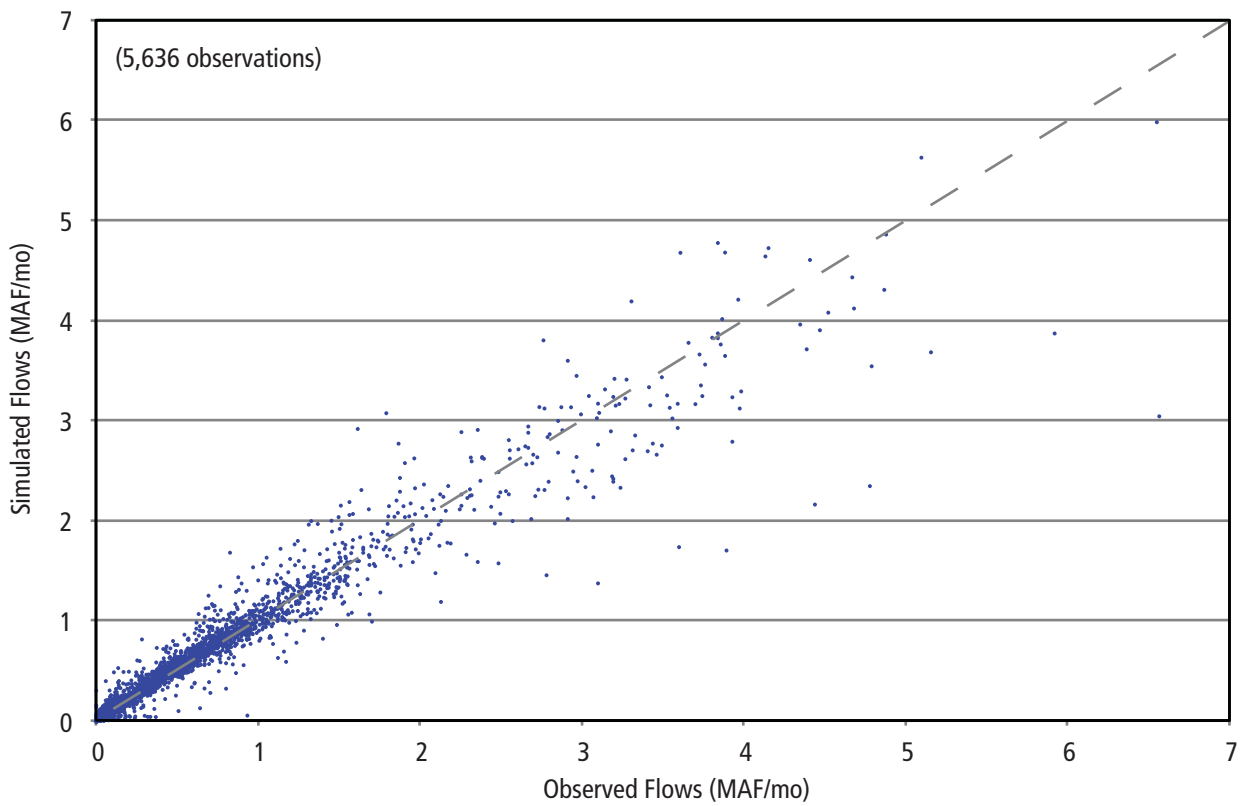


Table 8. C2VSim model performance: Surface water flow observations.

Description	Observations	RMSE	Residual	RMSE / Qmax	Residual / Qmax	Nash-Sutcliffe
Sacramento River Basin						
Sacramento River at Red Bluff	337	57.4	-28.7	0.013	-0.006	0.99
Sacramento River at Ords Ferry	337	140.6	-45.7	0.022	-0.007	0.97
Sacramento River at Knights Landing	337	187.0	-26.5	0.071	-0.010	0.80
Feather River at Yuba City	109	48.5	-18.6	0.022	-0.008	0.98
Yuba River before Marysville	337	28.9	-14.0	0.018	-0.009	0.97
Feather River at Olivehurst	61	34.4	-12.6	0.020	-0.007	0.99
Sacramento River at Verona	337	319.3	-26.7	0.077	-0.006	0.86
Bear River at Wheatland	337	17.6	-9.2	0.061	-0.032	0.86
American River at Fiar Oaks	337	3.5	-0.7	0.002	-0.000	1.00
Sacramento River at Freeport	337	393.1	-7.6	0.063	-0.001	0.87
Cache Creek near Woodland	337	27.9	6.0	0.039	0.008	0.90
	3,203	182.7	-17.0	0.028	-0.003	
Eastside Streams Region						
Dry Creek near Galt	241	13.7	-0.2	0.086	-0.001	0.57
Consumnes River at McConnell	86	11.3	-6.3	0.044	-0.025	0.95
Mokelumne River at Woodbridge	313	16.2	-12.5	0.056	-0.043	0.89
	640	14.7	-7.0	0.050	-0.024	
San Joaquin River Basin						
San Joaquin River near Mendota	45	30.3	-19.1	0.840	-0.529	-9.59
Merced River at Stevinson	265	8.5	1.4	0.025	0.004	0.98
Tuolomne River at Merced	337	76.4	10.2	0.080	0.011	0.70
San Joaquin River at Crows Landing	96	97.7	-59.9	0.063	-0.039	0.86
Orestimba Creek near Crows Landing	138	3.2	-0.7	0.080	-0.017	0.64
Stanislaus River at Ripon	238	9.3	2.0	0.031	0.007	0.97
San Joaquin River at Newman	337	107.7	-9.1	0.070	-0.006	0.78
San Joaquin River at Vernalis	337	127.6	-38.4	0.052	-0.016	0.89
	1793	83.0	-10.3	0.034	-0.004	
All flow observations	5,636	145.6	-13.7	0.022	-0.002	

Units for flow observations are acre-fet per month

Results and Discussion

California's Central Valley naturally receives water directly from precipitation and as inflow from the surrounding watersheds, and loses water to outflow through the Carquinez Strait to San Francisco Bay and to evapotranspiration. The groundwater system acts as an underground storage reservoir, storing water when surface water supplies are greater than demands, and contributing water to supplement supplies when demands are greater than supplies. With the more recent construction of the surface storage and conveyance infrastructure, the Central Valley water system includes surface water imports from the Trinity River Basin and exports to the San Francisco Bay area and Southern California.

The C2VSim model uses a database of historical land use and crop acreages, precipitation and evapotranspiration rates, surface water inflows and exports, and surface water diversions to simulate the Central Valley integrated groundwater and surface water system and calculate monthly water budgets for 21 Central Valley subregions from October 1921 to September 2009. Model results show how the increase in agricultural and urban land use, development of the surface water storage and distribution system and widespread groundwater pumping altered the hydrologic system. Dam construction has altered the flow regime in river systems, reducing winter and spring flows and increasing summer flows. Increased groundwater pumping has lowered the water table, resulting in the removal of approximately 130 MAF of groundwater from storage during this period.

Table 9. C2VSim output files.

File Name	File contents
Simulation program output files	
CVSubsHyd.out	Subdicence hydrographs
CVAvgET.out	Virtual crop characteristics
CVtiledrn.out	Tile drain/subsurface irrigation hydrographs
CVSWhyd.out	Stream flow hydrographs
CVGWhyd.out	Groundwater level hydrographs
CVGWheadall.out	Groundwater level at each model node
CVGWheadTecPlot.out	Groundwater heads for the TecPlot program
CVSubsidTecPlot.out	Subsidence output for the TecPlot progam
CVfinallist.out	Final simulation state
Budget program output files	
CVsmwshed.bud	Small watershed flow components
Cvdiverdtl.bud	Diversion details
CVstreamrch.bud	Stream budget by reach
CVlake.bud	Lake budget
CVlandwater.bud	Land and water use budget
CVstream.bud	Stream budget
CVrootzn.bud	Root zone moisture budget
Cvground.bud	Groundwater budget
Z-Budget program output files	
Zbudget_All.bud	Model area
Zbudget_HRs.bud	Hydrologic regions
Zbudget_SRs.bud	Subregions

Central Valley Water Budget

The C2VSim model produces several budget tables, which present water balances for specific model components (Table 9). The information in these output files can be summarized for any time period from one month up to the full model run period to produce water budgets for each model subregion, hydrologic regions comprising several subregions, or the entire model area. Table 10 is summary table listing annual average flows for the full simulation period, water years 1922 to 2009. It is often more instructive to look at changes through time rather than long-term average values. The discussion in this section will generally focus on three time periods – the 1920's, 1960's and 2000's – which represent the first, middle and last decade of the C2VSim simulation period. Average annual values for each decade illustrate how the hydrologic system has

Table 10. Average Annual Central Valley Basin Flows from the C2VSim model for Water Years 1922-2009.

Hydrologic Region	C2VSIM Subregion	DSA	Area (mi^2)	Precipitation	Total Evapo-transpiration	Surface Water Inflows*	Surface Water Outflows*	Agricultural Demand	Ag Surface Water Deliveries	Ag Groundwater Pumpage	M&I Demand	M&I Surface Water Deliveries	M&I Groundwater Pumpage	Groundwater Discharge to Rivers	Small Watershed Baseflow	Groundwater Recharge	Change in Groundwater Storage	Subsidence Volume	Interbasin Groundwater Flow
1. Sacramento Valley																			
	1	58	513	874,939	690,273	7,937,634	8,537,555	44,511	101,795	5,396	31,659	10,727	20,955	143,318	86,702	64,086	-18,871	11	-18,869
	2	10	1,091	1,331,009	1,269,999	10,116,279	9,858,824	267,177	148,518	220,119	20,417	0	20,417	100,278	80,652	194,616	-65,304	242	-165
	3	12	1,077	1,041,915	1,360,219	0	588,186	652,757	987,673	83,957	6,055	0	6,055	174,589	49,578	216,295	2,811	1,539	-35,537
	4	15	549	533,818	890,121	10,447,009	8,043,984	430,668	609,662	92,538	2,879	0	2,879	168,893	0	259,636	-3,288	1,386	40,056
	5	69	959	1,158,762	1,623,254	6,315,181	8,614,006	779,553	965,011	243,706	42,327	16,181	26,919	-53,910	17,997	174,015	-24,544	160	22,309
	6	65	1,028	1,065,896	1,202,325	611,095	3,232,330	356,179	247,569	235,810	33,223	19,615	14,586	-86,603	50,413	99,074	-9,923	4,384	-41,649
	7	70	547	595,540	828,973	19,293,020	17,021,251	320,748	256,308	246,359	119,159	87,461	35,876	-88,024	84,366	65,180	-44,298	367	31,303
	TOTAL		5,763	6,601,878	7,865,165	*	*	2,851,592	3,316,537	1,127,885	255,720	133,984	127,688	358,541	369,708	1,072,902	-163,417	8,088	*
2. Eastside Streams																			
	8	59	1,399	1,346,252	1,552,004	1,103,725	1,256,366	499,349	98,522	582,151	112,675	47,451	65,830	-231,848	113,590	166,663	-135,304	575	87,779
3. Sacramento-San Joaquin Delta																			
	9	55	1,134	887,264	1,597,535	25,972,879	24,124,933	735,885	898,289	209,558	46,487	41,756	4,827	-97,898	15,228	76,141	-24,828	292	-21,284
4. San Joaquin Basin																			
	10	49A	1,044	540,454	1,240,573	4,242,007	4,462,931	718,591	900,932	250,272	14,467	10,192	8,046	101,322	29,966	320,692	-1,499	35,341	-44,445
	11	49B	645	470,683	923,415	2,269,747	1,811,651	483,928	692,687	79,140	51,434	6,961	44,475	209,785	18,069	296,765	-18,525	43	-81,309
	12	49C	532	364,157	760,818	939,436	669,260	399,289	520,423	97,832	23,251	0	23,251	91,971	2,520	199,791	-10,732	11	4,125
	13	49D	1,621	1,037,127	1,933,692	1,096,604	1,273,064	947,653	629,300	650,052	41,345	2,432	38,959	-178,430	13,666	351,934	-135,496	9,485	55,191
	TOTAL		3,842	2,412,421	4,858,497	*	*	2,549,461	2,743,343	1,077,296	130,496	19,585	114,731	224,648	64,222	1,169,182	-166,251	44,880	*
5. Tulare Basin																			
	14	60A	1,047	395,440	1,229,298	0	0	740,133	421,528	594,263	11,669	2,533	9,823	-72,971	20,845	132,271	-256,953	122,415	72,287
	15	60B	1,413	540,238	1,932,319	823,035	710,591	1,264,772	608,941	1,133,522	26,859	1,098	25,761	-461,542	3,974	395,478	-152,787	75,255	378,722
	16	60C	473	280,707	536,025	0	0	262,490	383,188	70,445	97,048	19,041	81,315	148,374	8,398	253,979	-35,869	1,890	-159,022
	17	60D	583	352,466	724,098	1,643,649	410,947	417,539	323,737	271,159	28,459	1,314	27,159	102,455	4,286	319,183	-74,841	2,463	-99,984
	18	60E	1,402	713,666	1,635,162	554,408	210,614	884,413	771,186	503,512	59,734	13,971	47,010	191,386	23,989	603,243	-53,601	61,075	-207,849
	19	60F	1,252	417,759	1,235,782	118,878	201,474	750,425	168,414	746,918	9,254	1,578	7,701	-70,347	4,158	364,242	-250,600	65,272	106,110
	20	60G	662	264,230	716,755	0	0	391,378	154,543	335,422	23,589	66,947	2,667	126,381	51,130	151,003	-213,264	49,073	-149,524
	21	60H	1,020	341,117	1,405,591	715,733	118,878	931,728	330,742	894,459	67,242	7,326	60,118	-102,741	56,152	335,109	-433,369	36,746	61,753
	TOTAL		7,852	3,305,623	9,415,029	*	*	5,642,876	3,162,279	4,549,698	323,853	113,808	261,553	-139,005	172,932	2,554,508	-1,471,284	414,188	*
Central Valley			19,989	14,553,437	25,288,231	27,412,695	24,359,223	12,279,163	10,218,969	7,546,589	869,231	356,584	574,630	114,439	735,680	5,039,395	-1,961,084	468,023	*

Groundwater Flows to Rivers = Stream-Aquifer + Lake-Aquifer + Tile Drains

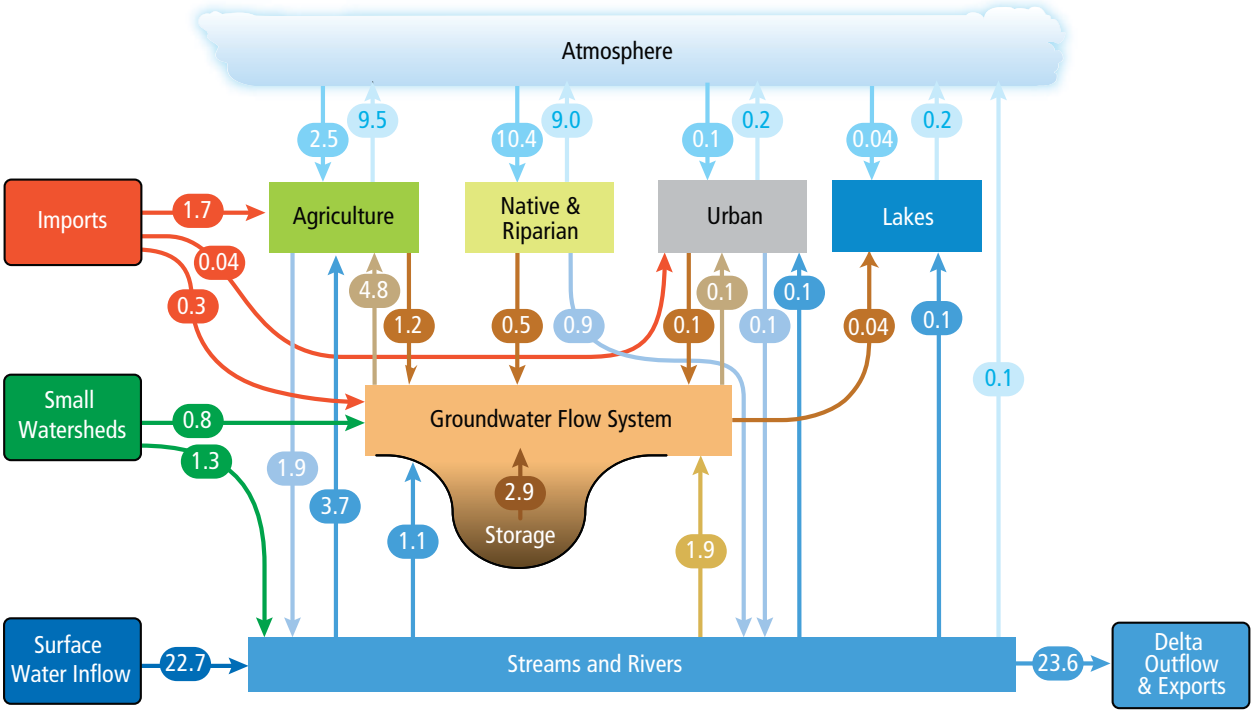
Recharge = Net Deep Percolation + Small Watershed Baseflow + Small Watershed Percolation + Diversion Recoverable Loss + Bypass Recoverable Loss

** Surface water inflows and outflows and interbasin flows do not add up across subregions or hydrologic regions*

changed over this time period. Annual differences within these decades, on the other hand, illustrate how climatic variability affects the hydrologic system. Although the hydrologic system has been modified and is extensively managed to smooth out water supplies between wet and dry years, annual variations in precipitation still have significant impacts on both water demands and water flows in the Central Valley.

Figures 43A-C combine information from several C2VSim output tables into a single water budget figure that presents average annual flows for each decade. These figures and summary water budget tables of average values for the 1920s, 1960s and 2000s (Tables 11, 12 and 13) show how the Central Valley hydrologic system has changed through time. Within the Central Valley, water inputs are dominated by precipitation and surface water inflows. Average annual precipitation and surface water inflow volumes have remained fairly constant over this time period. The largest changes have been the amount of water consumed by agricultural and urban users, and the corresponding increases in surface water diversions, surface water imports and groundwater pumping.

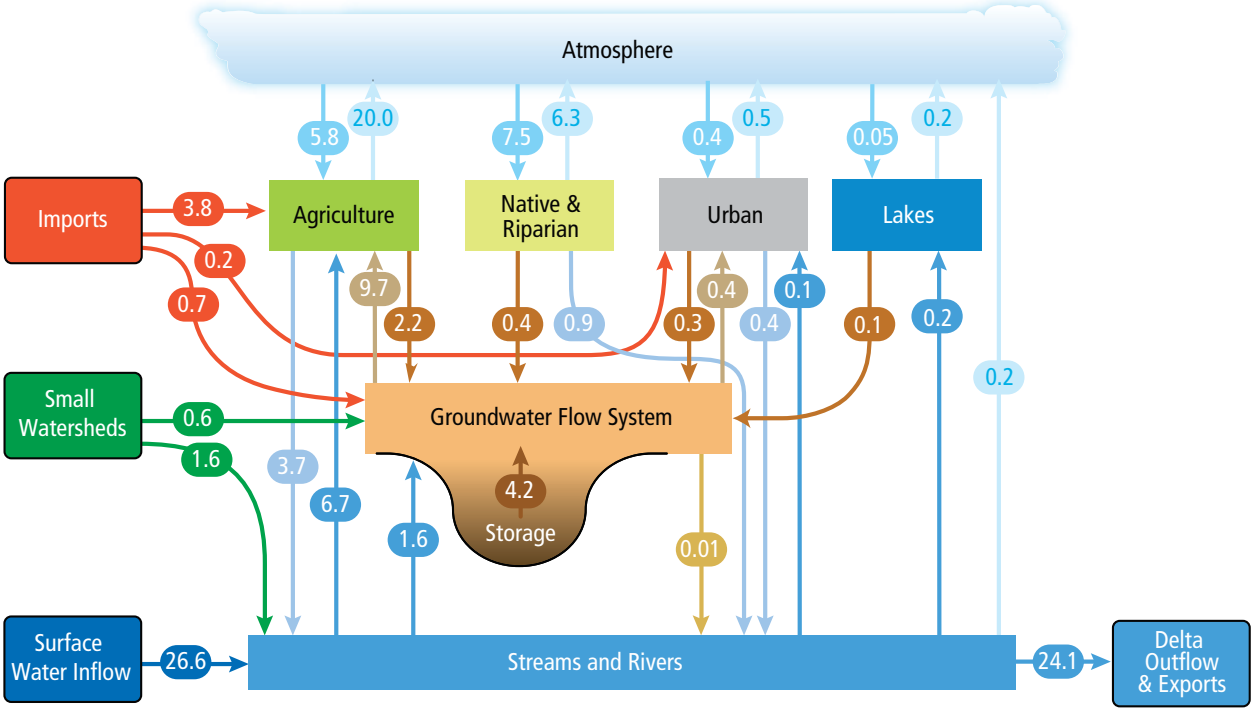
Figure 43A. Simulated water budget for California's Central Valley, 1922-1929.



*Note: Values may not add up due to rounding and changes in storage.

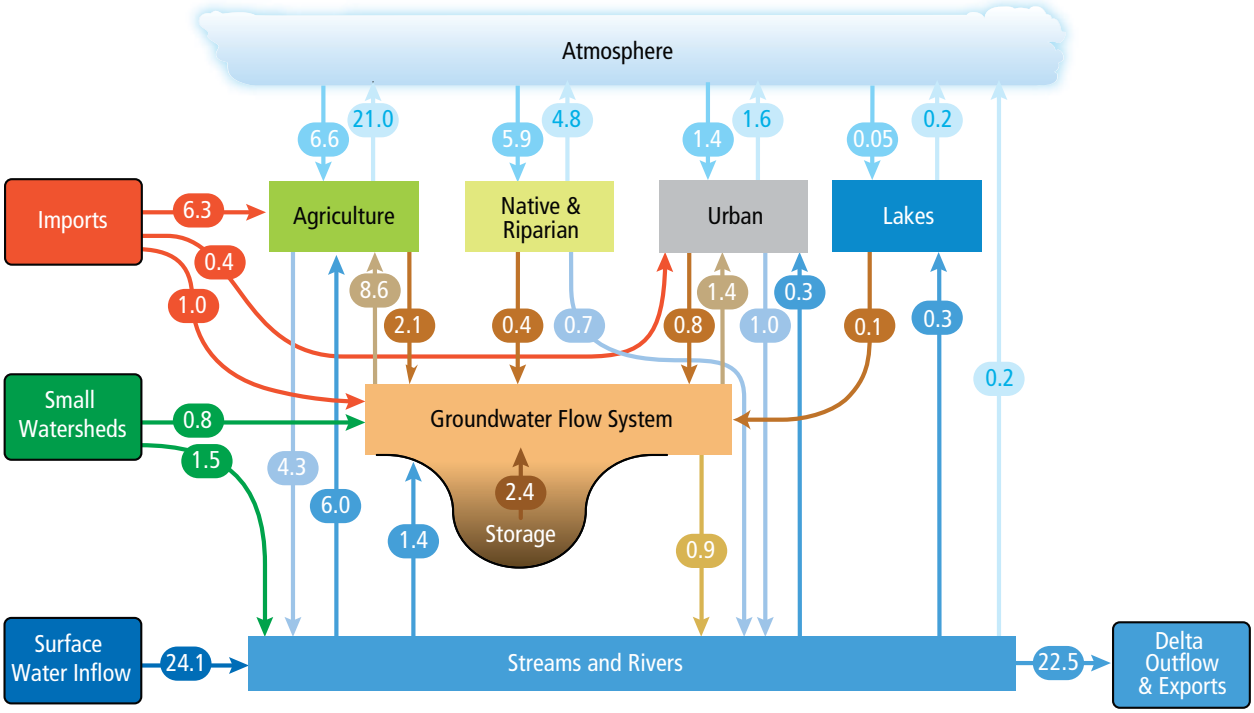
[Million Acre-Feet/Year]

Figure 43B. Simulated water budget for California's Central Valley, 1960-1969.



*Note: Values may not add up due to rounding and changes in storage. [Million Acre-Feet/Year]

Figure 43C. Simulated water budget for California's Central Valley, 2000-2009.



*Note: Values may not add up due to rounding and changes in storage. [Million Acre-Feet/Year]

Table 11. Central Valley Basin Flows from the C2VSim model for Water Years 1922-1929.

Hydrologic Region	C2VSIM Subregion	DSA	Area (mi²)	Precipitation	Total Evapo-transpiration	Surface Water Inflows*	Surface Water Outflows*	Agricultural Demand	Ag Surface Water Deliveries	Ag Groundwater Pumpage	M&I Demand	M&I Surface Water Deliveries	M&I Groundwater Pumpage	Groundwater Discharge to Rivers	Small Watershed Baseflow	Groundwater Recharge	Change in Groundwater Storage	Subsidence Volume	Interbasin Groundwater Flow
1. Sacramento Valley																			
	1	58	513	656,441	545,494	4,524,314	4,991,556	30,548	59,287	2,165	2,380	648	1,731	171,703	142,188	48,941	15,538	7	-4,898
	2	10	1,091	945,381	885,328	5,908,015	6,114,179	106,118	63,163	86,403	4,700	0	4,700	225,276	71,576	94,048	-150,426	328	-19,157
	3	12	1,077	757,542	756,320	0	447,969	227,648	357,518	33,976	2,310	0	2,310	134,035	33,970	161,614	28,809	3,545	-11,445
	4	15	549	400,967	493,794	6,562,148	5,981,886	141,873	267,904	10,775	970	0	970	122,728	0	136,786	3,768	1,454	66,477
	5	69	959	868,139	981,942	4,511,891	5,083,848	293,149	423,883	50,220	8,840	11,985	813	74,088	12,690	95,219	-17,106	106	-5,074
	6	65	1,028	763,917	730,926	318,378	1,467,813	84,051	91,636	39,638	4,020	0	4,020	78,081	37,504	58,676	-23,337	2,223	-57,024
	7	70	547	448,730	544,613	12,873,099	11,956,211	160,416	110,540	123,339	11,930	20,001	18	-28,727	58,383	28,129	-7,867	252	16,252
	TOTAL		5,763	4,841,117	4,938,417	*	*	1,043,803	1,373,931	346,515	35,150	32,635	14,563	777,184	356,310	623,414	-150,622	7,916	*
2. Eastside Streams																			
	8	59	1,399	949,816	1,021,567	824,922	897,682	232,552	64,414	254,846	18,760	21,024	532	-6,712	79,674	122,137	-46,668	187	-22,708
3. Sacramento-San Joaquin Delta																			
	9	55	1,134	626,975	1,150,179	18,548,558	18,083,170	526,279	591,881	162,916	16,130	15,001	1,129	-61,823	7,323	42,585	-52,189	125	63,200
4. San Joaquin Basin																			
	10	49A	1,044	376,641	656,412	4,233,784	4,226,852	313,200	453,347	114,589	2,690	0	2,690	55,694	18,282	177,249	32,288	17,796	-6,797
	11	49B	645	332,161	518,826	1,675,559	1,519,623	196,456	410,388	19,470	7,800	0	7,800	178,166	14,850	191,590	1,001	-2	-25,378
	12	49C	532	259,568	435,040	641,815	597,814	180,089	316,486	12,215	3,390	0	3,390	112,495	2,103	131,379	5,380	-3	-6,361
	13	49D	1,621	757,374	1,129,663	1,242,641	1,482,083	423,659	306,333	285,665	7,370	0	7,370	48,231	9,789	202,665	-128,030	782	3,798
	TOTAL		3,842	1,725,744	2,739,941	*	*	1,113,403	1,486,553	431,939	21,250	0	21,250	394,586	45,025	702,883	-89,360	18,573	*
5. Tulare Basin																			
	14	60A	1,047	275,458	623,311	0	0	318,725	0	373,426	3,100	0	3,100	23,275	9,554	31,825	-282,448	76,065	-23,321
	15	60B	1,413	382,847	1,049,770	849,826	730,014	631,590	186,538	667,338	5,210	0	5,210	-276,520	1,798	180,829	-199,928	28,836	305,509
	16	60C	473	193,698	313,935	0	0	127,216	138,079	77,511	19,260	0	19,260	79,773	4,111	90,652	-80,728	1,053	-73,955
	17	60D	583	245,942	394,780	1,027,756	573,815	162,749	92,789	134,737	5,460	0	5,460	80,012	1,356	110,207	-108,119	526	-79,924
	18	60E	1,402	487,814	904,111	287,312	134,512	404,631	148,557	383,103	12,560	0	12,560	118,708	15,085	266,331	-196,135	36,820	-94,874
	19	60F	1,252	281,625	681,781	46,442	141,500	377,613	49,351	413,283	1,990	0	1,990	-2,940	2,702	207,558	-182,285	19,788	75,904
	20	60G	662	174,389	340,382	0	0	146,523	30,412	152,084	4,600	1,791	3,294	104,283	21,910	24,702	-191,683	21,366	-117,573
	21	60H	1,020	223,281	699,120	383,063	46,442	442,880	164,427	407,047	12,260	7,592	6,309	-4,782	25,931	169,641	-196,063	32,520	17,352
	TOTAL		7,852	2,265,054	5,007,191	*	*	2,611,926	810,152	2,608,529	64,440	9,383	57,183	121,807	82,448	1,081,746	-1,437,389	216,975	*
Central Valley			19,989	10,408,706	14,857,295	18,167,174	18,184,620	5,527,964	4,326,930	3,804,745	155,731	78,043	94,658	1,225,043	570,780	2,572,765	-1,776,229	243,776	*

Groundwater Flows to Rivers = Stream-Aquifer + Lake-Aquifer + Tile Drains

Recharge = Net Deep Percolation + Small Watershed Baseflow + Small Watershed Percolation + Diversion Recoverable Loss + Bypass Recoverable Loss

** Surface water inflows and outflows and interbasin flows do not add up across subregions or hydrologic regions*

Table 12. Central Valley Basin Flows from the C2VSim model for Water Years 1960-1969.

Hydrologic Region	C2VSIM Subregion	DSA	Area (mi²)	Precipitation	Total Evapo-transpiration	Surface Water Inflows*	Surface Water Outflows*	Agricultural Demand	Ag Surface Water Deliveries	Ag Groundwater Pumpage	M&I Demand	M&I Surface Water Deliveries	M&I Groundwater Pumpage	Groundwater Discharge to Rivers	Small Watershed Baseflow	Groundwater Recharge	Change in Groundwater Storage	Subsidence Volume	Interbasin Groundwater Flow
1. Sacramento Valley																			
	1	58	513	811,750	674,505	8,091,392	8,603,731	38,410	110,411	1,095	19,710	6,261	13,449	147,464	69,459	69,892	-22,647	10	-22,313
	2	10	1,091	1,235,157	1,265,597	10,145,295	9,791,419	308,864	159,705	267,961	16,070	0	16,070	47,034	75,762	194,027	-60,837	439	16,247
	3	12	1,077	946,861	1,337,517	0	527,809	691,559	1,064,310	33,750	4,650	0	4,650	220,113	37,371	215,896	-4,450	797	-51,415
	4	15	549	483,242	883,796	10,319,228	8,505,443	466,597	720,381	53,367	2,380	0	2,380	283,665	0	326,226	-12,624	562	18,351
	5	69	959	1,088,829	1,672,468	6,233,878	7,499,191	858,467	1,043,509	218,396	34,340	12,171	22,169	-28,504	16,631	169,761	-25,521	148	33,663
	6	65	1,028	1,005,431	1,280,299	530,472	2,370,674	481,997	264,305	372,435	22,050	17,517	7,219	-200,297	43,422	110,348	-16,695	8,892	-8,929
	7	70	547	571,700	810,390	18,535,847	16,875,423	325,046	279,385	231,203	95,301	79,206	17,679	-66,319	81,239	67,252	-33,816	256	13,383
	TOTAL		5,763	6,142,971	7,924,572	*	*	3,170,939	3,642,006	1,178,206	194,501	115,155	83,616	403,157	323,883	1,153,401	-176,590	11,105	*
2. Eastside Streams																			
	8	59	1,399	1,283,173	1,624,003	968,496	1,108,762	614,270	107,561	732,404	101,551	34,368	67,186	-255,382	106,984	167,843	-268,214	1,166	105,364
3. Sacramento-San Joaquin Delta																			
	9	55	1,134	833,582	1,680,756	24,048,818	22,376,222	850,280	1,084,878	215,321	34,510	32,095	2,416	-107,140	11,373	82,539	-16,242	443	-41,863
4. San Joaquin Basin																			
	10	49A	1,044	520,223	1,243,265	3,385,400	3,693,958	752,687	1,074,956	134,890	11,100	20,908	969	181,534	26,535	366,948	57,883	18,850	-121,147
	11	49B	645	450,894	1,030,635	2,194,008	1,673,481	615,990	755,931	129,598	34,460	0	34,460	179,320	17,694	284,540	-41,066	78	-71,060
	12	49C	532	351,023	783,680	858,026	514,569	442,817	517,838	123,733	15,660	0	15,660	70,286	2,407	186,047	-21,231	-6	16,281
	13	49D	1,621	1,021,370	2,055,579	644,205	772,099	1,085,318	733,059	725,131	32,560	1,449	31,115	-234,784	13,563	360,466	-133,013	14,422	69,928
	TOTAL		3,842	2,343,511	5,113,159	*	*	2,896,812	3,081,784	1,113,352	93,781	22,357	82,205	196,357	60,199	1,198,001	-137,428	33,344	*
5. Tulare Basin																			
	14	60A	1,047	377,505	1,346,208	0	0	907,740	47,545	1,021,875	10,530	0	10,530	-136,790	12,669	46,154	-503,986	335,325	135,531
	15	60B	1,413	521,873	2,206,753	801,452	635,281	1,582,855	512,968	1,595,539	19,580	94	19,486	-572,564	3,681	410,921	-344,473	218,890	436,179
	16	60C	473	278,177	615,981	0	0	354,184	418,921	122,004	72,431	35,382	54,003	145,084	6,431	257,066	-55,012	2,582	-163,678
	17	60D	583	340,723	790,549	1,663,656	375,054	498,953	398,654	287,303	21,130	3,504	17,741	149,686	2,750	331,153	-115,704	5,124	-151,583
	18	60E	1,402	702,885	1,810,466	571,845	194,862	1,094,301	769,843	711,261	47,060	30,668	21,216	136,079	21,863	589,037	-124,098	133,558	-217,658
	19	60F	1,252	397,949	1,432,709	190,287	231,536	978,811	82,329	1,106,377	8,510	0	8,510	-166,041	3,408	357,320	-456,703	131,416	153,342
	20	60G	662	258,218	731,375	0	0	420,275	166,237	360,444	16,930	91,736	564	217,508	38,826	167,159	-293,226	79,305	-242,025
	21	60H	1,020	312,946	1,564,297	736,397	190,287	1,119,757	182,297	1,259,453	46,150	7,061	39,089	-174,143	34,462	252,952	-805,553	41,045	93,401
	TOTAL		7,852	3,190,276	10,498,337	*	*	6,956,877	2,578,795	6,464,256	242,322	168,445	171,139	-401,180	124,089	2,411,762	-2,698,754	947,245	*
Central Valley			19,999	13,793,512	26,840,827	26,575,123	22,596,222	14,489,179	10,495,024	9,703,540	666,665	372,420	406,561	-164,189	626,528	5,013,545	-3,297,228	993,303	*

Groundwater Flows to Rivers = Stream-Aquifer + Lake-Aquifer + Tile Drains

Recharge = Net Deep Percolation + Small Watershed Baseflow + Small Watershed Percolation + Diversion Recoverable Loss + Bypass Recoverable Loss

** Surface water inflows and outflows and interbasin flows do not add up across subregions or hydrologic regions*

Table 13. Central Valley Basin Flows from the C2VSim model for Water Years 2000-2009.

Hydrologic Region	C2VSIM Subregion	DSA	Area (mi²)	Precipitation	Total Evapo-transpiration	Surface Water Inflows*	Surface Water Outflows*	Agricultural Demand	Ag Surface Water Deliveries	Ag Groundwater Pumpage	M&I Demand	M&I Surface Water Deliveries	M&I Groundwater Pumpage	Groundwater Discharge to Rivers	Small Watershed Baseflow	Groundwater Recharge	Change in Groundwater Storage	Subsidence Volume	Interbasin Groundwater Flow
1. Sacramento Valley																			
	1	58	513	795,273	655,376	8,243,793	8,808,276	77,100	88,389	27,919	91,481	25,637	65,848	68,755	77,151	48,581	-36,770	20	-18,229
	2	10	1,091	1,305,474	1,352,581	10,382,007	9,748,904	369,425	175,392	322,510	44,980	0	44,980	-12,759	86,314	221,606	-46,656	154	-9,304
	3	12	1,077	1,089,754	1,729,995	0	774,948	1,003,636	1,281,030	235,900	12,040	0	12,040	82,597	68,215	210,445	-49,985	1,892	-13,457
	4	15	549	539,111	1,074,006	10,523,852	8,356,437	620,260	654,745	233,970	5,410	0	5,410	30,014	0	252,694	-15,146	1,556	940
	5	69	959	1,101,001	1,882,298	4,833,329	6,920,768	1,099,488	1,352,083	468,825	91,141	22,347	68,798	-242,342	19,375	244,849	-30,978	79	36,627
	6	65	1,028	1,094,849	1,345,256	478,973	2,258,947	467,044	358,379	278,384	85,641	51,659	34,015	-115,153	61,102	106,334	-27,967	1,843	-55,163
	7	70	547	544,172	910,071	17,455,831	15,886,567	415,676	290,896	371,939	268,772	186,325	82,801	-181,273	87,765	89,131	-95,922	650	70,852
	TOTAL		5,763	6,469,634	8,949,582	*	*	4,052,629	4,200,914	1,939,448	599,464	285,967	313,893	-370,162	399,922	1,173,639	-303,425	6,194	*
2. Eastside Streams																			
	8	59	1,399	1,247,115	1,561,037	835,570	986,550	550,437	97,986	642,427	234,492	85,213	149,287	-378,940	119,844	151,694	-140,715	521	179,604
3. Sacramento-San Joaquin Delta																			
	9	55	1,134	884,226	1,422,024	22,101,888	18,886,011	575,529	702,999	177,850	104,011	88,481	15,820	-80,853	21,041	80,812	-10,770	193	-102,442
4. San Joaquin Basin																			
	10	49A	1,044	508,561	1,433,893	2,681,517	2,969,824	861,330	1,014,040	368,368	35,440	9,111	26,336	51,720	32,419	364,884	-47,107	28,290	-13,637
	11	49B	645	424,133	941,060	1,948,977	1,313,173	501,029	662,342	85,963	132,861	42,857	90,011	191,879	17,098	324,881	-25,841	32	-130,371
	12	49C	532	324,825	860,329	870,993	489,389	504,502	565,365	169,463	60,080	0	60,083	30,425	2,409	227,016	-30,521	24	15,878
	13	49D	1,621	946,368	2,005,744	530,910	590,575	1,037,214	540,453	805,905	92,211	7,848	84,442	-276,974	12,600	345,195	-242,128	13,450	77,117
	TOTAL		3,842	2,203,888	5,241,026	*	*	2,904,076	2,782,200	1,429,698	320,592	59,816	260,871	-2,950	64,526	1,261,977	-345,596	41,796	*
5. Tulare Basin																			
	14	60A	1,047	383,992	1,384,787	0	0	840,533	848,325	430,725	22,180	10,707	12,992	-60,423	25,808	254,932	-87,843	15,570	59,994
	15	60B	1,413	511,945	2,039,033	558,121	565,104	1,319,055	674,035	1,146,980	67,890	3,042	64,849	-493,430	3,729	447,551	-122,783	12,965	395,655
	16	60C	473	259,498	565,413	0	0	262,347	423,286	29,451	222,232	47,815	174,761	195,874	9,602	336,965	-51,257	2,263	-216,227
	17	60D	583	320,971	823,604	1,522,582	279,124	517,266	306,798	352,205	66,340	1,734	64,607	-16,723	4,866	296,650	-97,794	779	-34,436
	18	60E	1,402	617,055	1,812,558	489,009	188,025	1,060,907	1,333,704	298,993	131,401	3,006	128,396	415,379	23,736	750,114	-52,452	16,468	-344,435
	19	60F	1,252	368,732	1,221,191	93,471	90,972	751,951	174,929	729,138	17,460	2,825	14,792	-152,334	3,783	191,555	-318,534	77,722	114,393
	20	60G	662	231,563	888,223	0	0	563,825	210,617	488,527	57,460	106,879	2,343	58,187	52,255	197,980	-245,960	52,862	-78,514
	21	60H	1,020	318,590	1,578,028	617,917	93,471	1,034,730	490,559	895,135	171,971	6,590	165,384	-94,129	79,146	488,434	-364,617	33,025	65,156
	TOTAL		7,852	3,012,347	10,312,838	*	*	6,350,614	4,462,254	4,371,154	756,935	182,599	628,124	-147,600	202,925	2,964,179	-1,341,238	211,652	*
Central Valley			19,989	13,817,210	27,486,507	24,131,065	19,169,390	14,433,286	12,246,354	8,560,576	2,015,494	702,076	1,367,995	-980,504	808,258	5,632,301	-2,141,744	260,358	*

Groundwater Flows to Rivers = Stream-Aquifer + Lake-Aquifer + Tile Drains

Recharge = Net Deep Percolation + Small Watershed Baseflow + Small Watershed Percolation + Diversion Recoverable Loss + Bypass Recoverable Loss

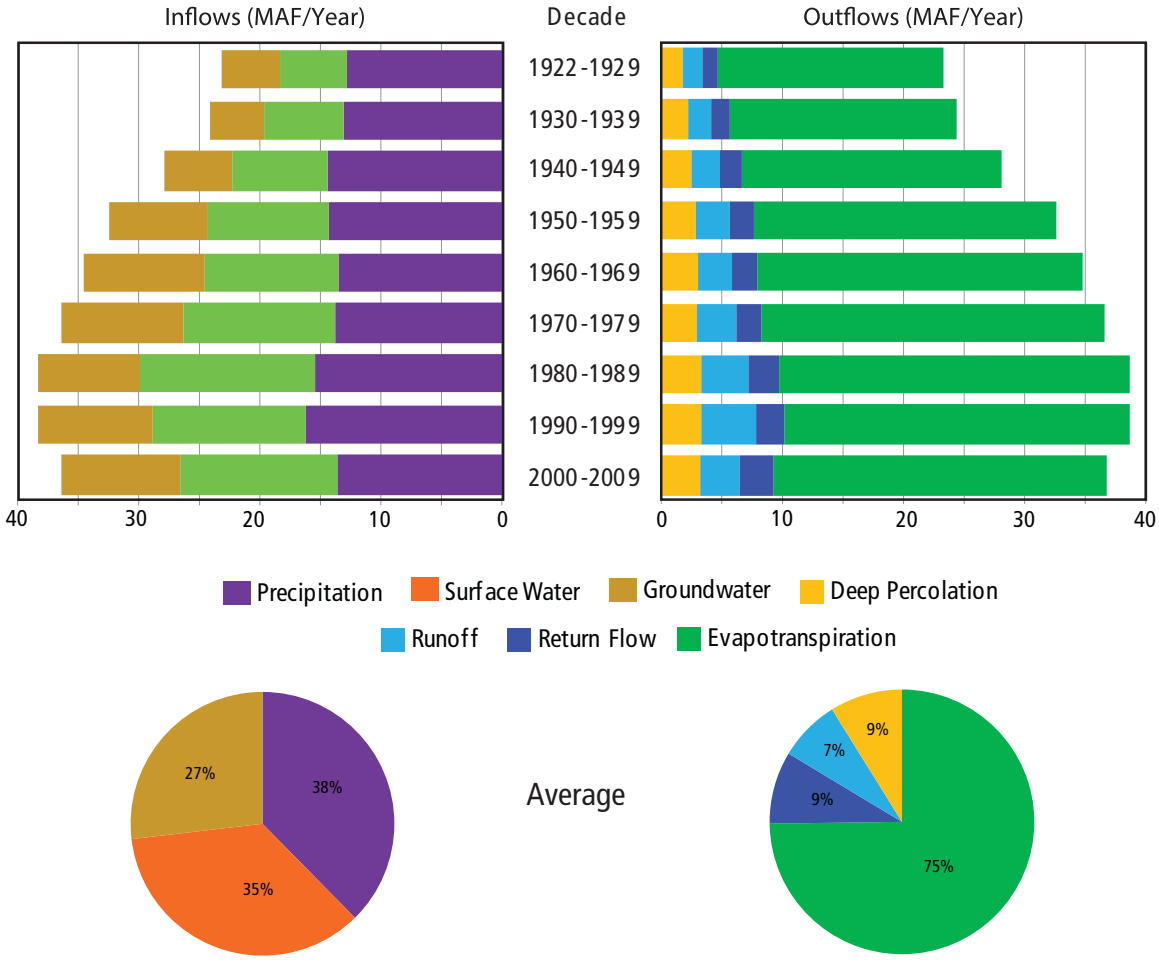
** Surface water inflows and outflows and interbasin flows do not add up across subregions or hydrologic regions*

Land Surface Water Balance

Annual Land Surface Process water balances for the entire model area for three decades demonstrate the significant hydrologic changes that have occurred in the Central Valley (Figure 44). The most notable change over this time has been the amount of water entering and passing through the system as a result of the conversion from native vegetation to agricultural and urban land use. The average volume of water evapotranspired each year in the Central Valley increased steadily from approximately 15 MAF/yr in the 1920s to 27 MAF/yr in the 1980s, and remained at 27 MAF/yr in the 2000s.

The proportions of the different inflow sources and outflow destinations have changed significantly from the 1920s to the 2000s. The annual volume of precipitation falling on the valley floor fluctuated between a low of 6 MAF in 1924 and a high of 29 MAF in 1998. The average annual precipitation volume is 14 MAF with a standard deviation of 5 MAF. Surface water diversion and groundwater pumping volumes increased significantly between the 1920s and 1980s, with surface

Figure 44. Land Surface Process budget for California's Central Valley for each decade, 1920s-2000s.



Note: Flow rates near zero may not appear on these figures.

water use slightly greater than groundwater use. In contrast, outflows are dominated by evapotranspiration. The proportion of outflows going to runoff declined and the proportion going to return flows increased as a result of the increased agricultural and urban area and reduced natural vegetation area.

Comparisons between annual land surface water budgets for the agricultural, urban and native vegetation land use classes for water years 2000-2009 (Figure 45) show the relative dominance of agricultural water use within the Central Valley. Total inflow and total outflow volumes fluctuate between 32 and 42 MAF/yr. This was dominated by the roughly 25-30 MAF/yr on agricultural lands, which comprised 53% of the total land area. Water flows through native and riparian vegetation ranged from 3.5-8.4 MAF/yr on 38% of the land area, and urban water flows of 3.0-4.2 MAF/yr. Agricultural and urban water inputs are dominated by applied water, and native vegetation relies solely on precipitation. The distribution of outflows also varies significantly between the land use classes. Evapotranspiration dominates in both agricultural and native vegetation, while for urban areas the sum of runoff, return flow and deep percolation is slightly greater than evapotranspiration. The share and volume of deep percolation is significantly greater for agriculture than for native vegetation, because water applications maintain a higher average soil moisture and because water applications allow deep percolation to occur throughout the year.

Figure 45A. Land Surface Process budget for Agriculture, 2000-2009.

Note: Flow rates near zero may not appear on these figures.

Figure 45B. Land Surface Process budget for Urban areas, 2000-2009.

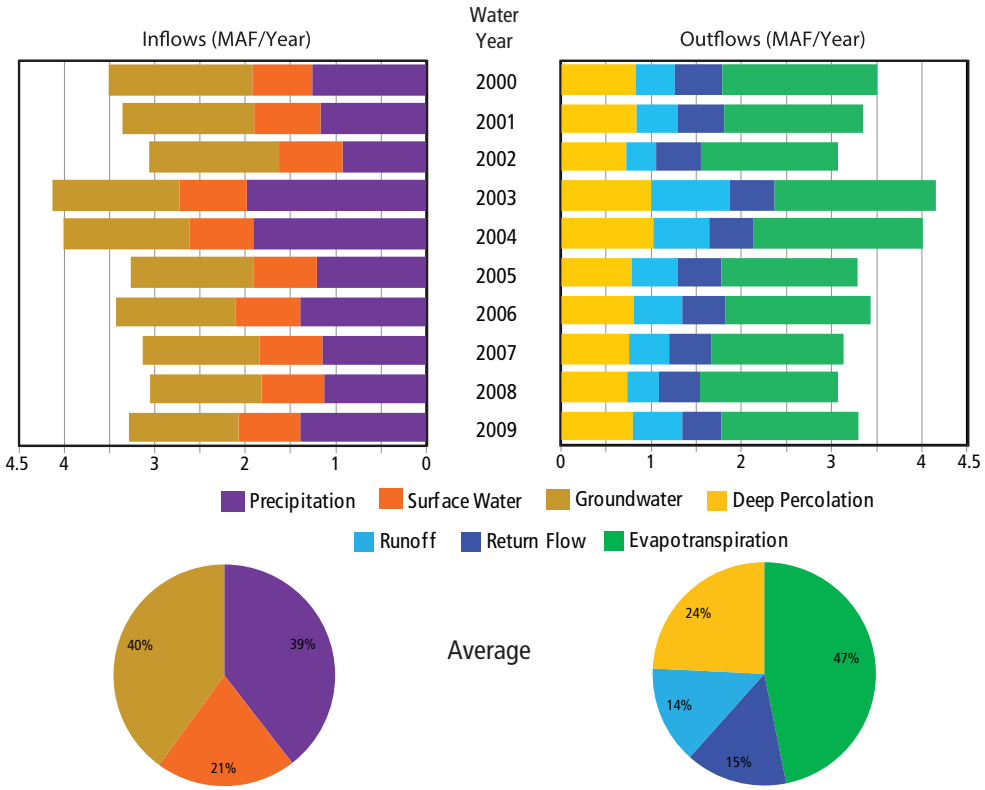
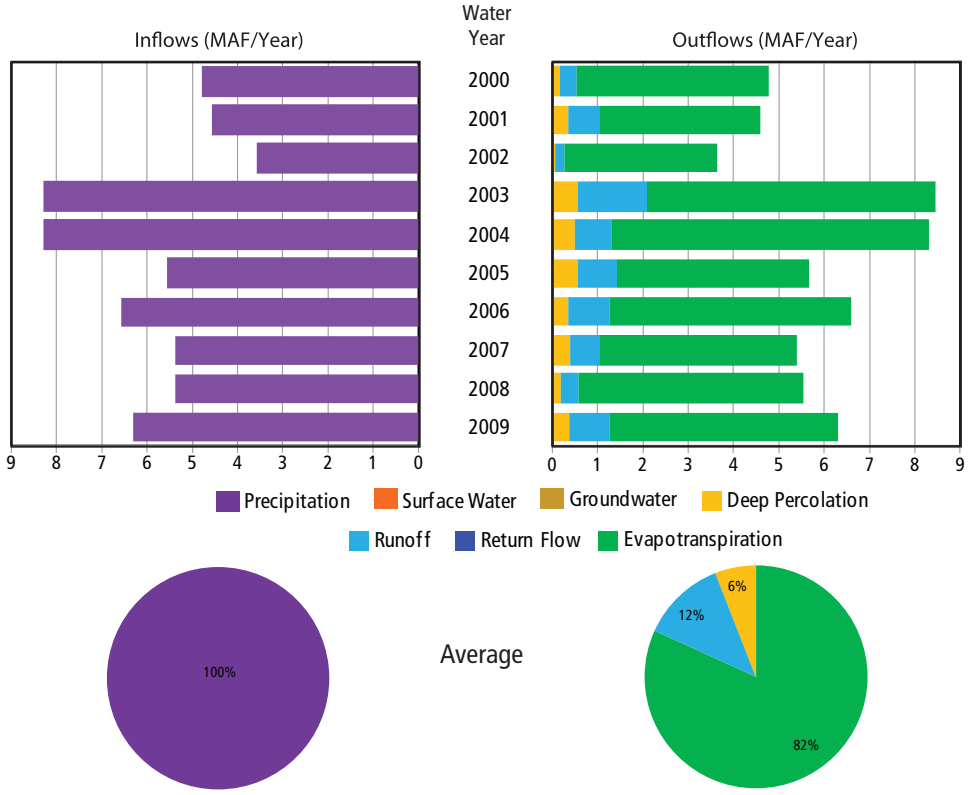


Figure 45C. Land Surface Process budget for Native and Riparian Vegetation, 2000-2009.

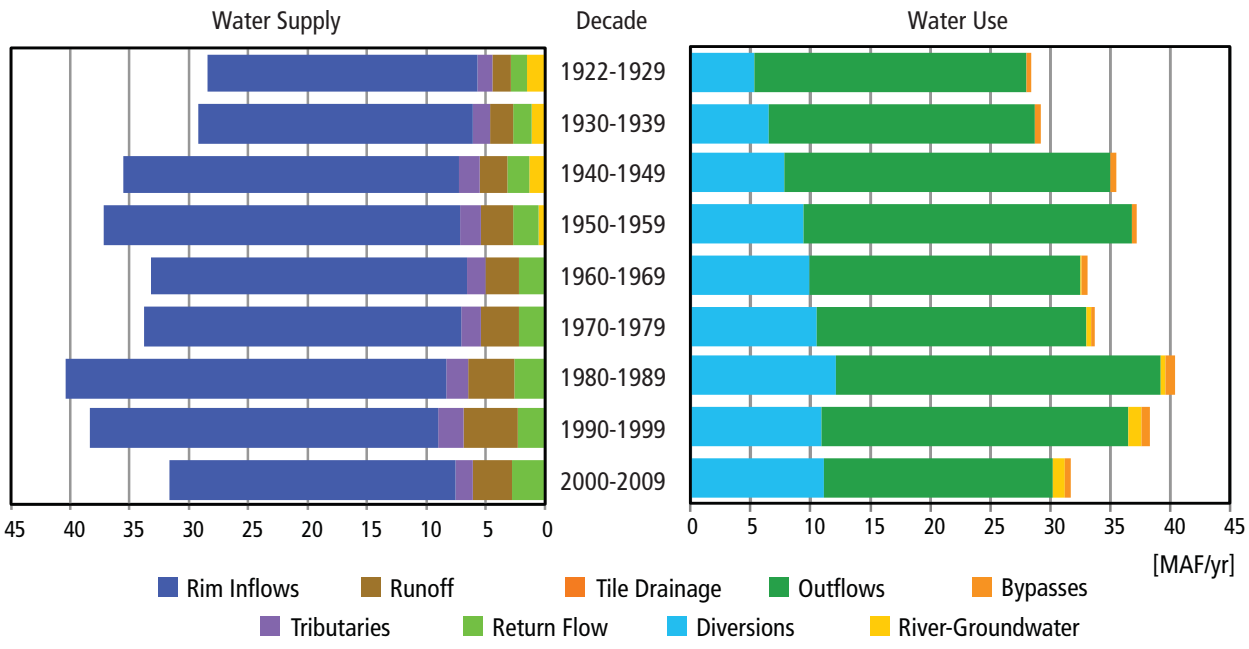


Note: Flow rates near zero may not appear on these figures.

River Flow System Water Balance

The average volume of water transported through the Central Valley river system each decade has varied between approximately 28 and 33 MAF/yr (Figure 40). Most of this water originates as precipitation in the watersheds surrounding the Central Valley, (represented as *River Inflows* in Figure 46) with some additional contributions from precipitation runoff in the valley (*Runoff*), surface water inflows from adjacent small-stream watersheds (*Tributaries*), inflows from groundwater to rivers (*River-Groundwater*), return flow from irrigation (*Return Flow*), and a very small amount from subsurface agricultural drains (*Tile Drainage*). Much of this water flows out through the Carquinez Strait to the San Francisco Bay and Pacific Ocean (*Outflows*), but a significant portion is diverted for agricultural and urban use (*Diversions*), and small portions flow from rivers to groundwater (*River-Groundwater*) and are recharged to groundwater through aquifer storage programs (simulated in C2VSim as a *Bypass*). Surface water diversions increased steadily between the 1920s and 1980s as agricultural and urban demands increased, then declined through the 2000s. At the same time, groundwater discharges to rivers decreased, and precipitation runoff and irrigation return flows increased.

Figure 46. Simulated sources and destinations for river water in California's Central Valley, 1920's-2000's.



In 1922, only a few of the 36 river inflows simulated in the C2VSim model had regulated flows and the dams were small by modern standards, with a total storage volume of less than 1 MAF. By 1980, large dams regulating flows had been constructed on 19 of the 36 rivers, with a total storage capacity of more than 20 MAF (Table 14). Several large off-stream reservoirs had also been constructed, and water was being

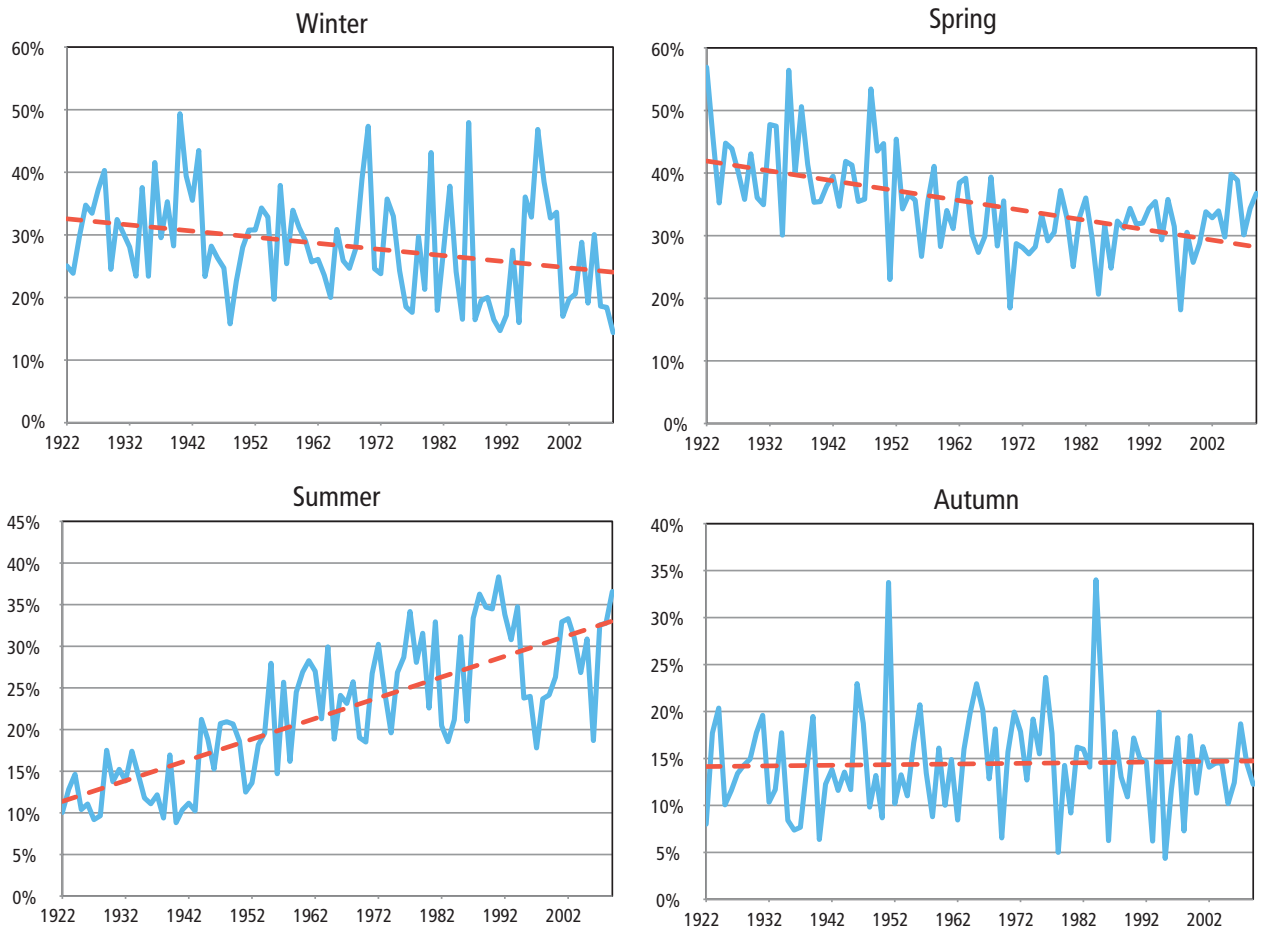
Table 14. The largest water storage reservoir in each river flowing to California's Central Valley.

River	Reservoir	Water Storage Volume (AF)	Owner	Year Completed
Cache Creek	Clear Lake	315,000	Yolo Co. Flood Ctrl. & Water Cons. Dist.	1914
San Joaquin River	Millerton Lake	520,500	U.S. Bureau of Reclamation	1942
Sacramento River	Lake Shasta	4,552,200	U.S. Bureau of Reclamation	1945
Kern River	Lake Isabella	568,000	U.S. Army Corps of Engineers	1953
Kings River	Pine Flat Lake	1,000,000	U.S. Army Corps of Engineers	1954
American River	Folsom Lake	975,000	U.S. Army Corps of Engineers	1956
Putah Creek	Lake Berryessa	1,602,000	U.S. Bureau of Reclamation	1958
Tule River	Lake Success	82,300	U.S. Army Corps of Engineers	1961
Kaweah River	Lake Kaweah	143,000	U.S. Army Corps of Engineers	1962
Mokelumne River	Camanche Reservoir	417,120	East Bay Municipal Utility District	1963
Calaveras River	New Hogan Lake	317,000	U.S. Army Corps of Engineers	1963
Stony Creek	Black Butte Reservoir	143,700	U.S. Army Corps of Engineers	1963
Bear River	Camp Far West Reservoir	104,500	South Sutter Water District	1963
Merced River	Lake McClure	1,032,000	Merced Irrigation District	1967
Feather River	Lake Oroville	3,537,577	CA Department of Water Resources	1968
Yuba River	New Bullards Bar Reservoir	969,600	Yuba County Water Authority	1970
Tuolumne River	New Don Pedro Reservoir	2,030,000	Modesto ID and Turlock ID	1971
Fresno River	Hensley Lake	90,000	U.S. Army Corps of Engineers	1974
Chowchilla River	Eastman Lake	150,000	U.S. Army Corps of Engineers	1975
Stanislaus River	New Melones Reservoir	2,400,000	U.S. Bureau of Reclamation	1979

(sorted by date)

imported from the Trinity River system. These dams allowed river inflows to the Central Valley to be regulated to coincide with agricultural demands. As a result, the proportion of annual river inflows occurring in the winter and spring has declined, and the proportion occurring in the summer has significantly increased (Figure 47).

Figure 47. Percentage of Central Valley inflows occurring in each season, 1922-2009.



A water balance omitting upstream inflows and downstream outflows, and showing only the volumes of water flowing into and out of the river system within the Central Valley for water years 2000-2009 (Figure 48), shows that surface water diversions are approximately double the other in-valley inflows. Surface water diversions fluctuated between approximately 10 and 15 MAF/yr during this decade, and inflows within the Central Valley varied between approximately 4.5 and 9 MAF/yr. Runoff from precipitation accounted for 54% of the inflows, and irrigation return flows for 45%. Groundwater discharges into rivers accounted for 1% of inflows, but varied significantly between net flows to groundwater (or a negative inflow) and discharge from groundwater.

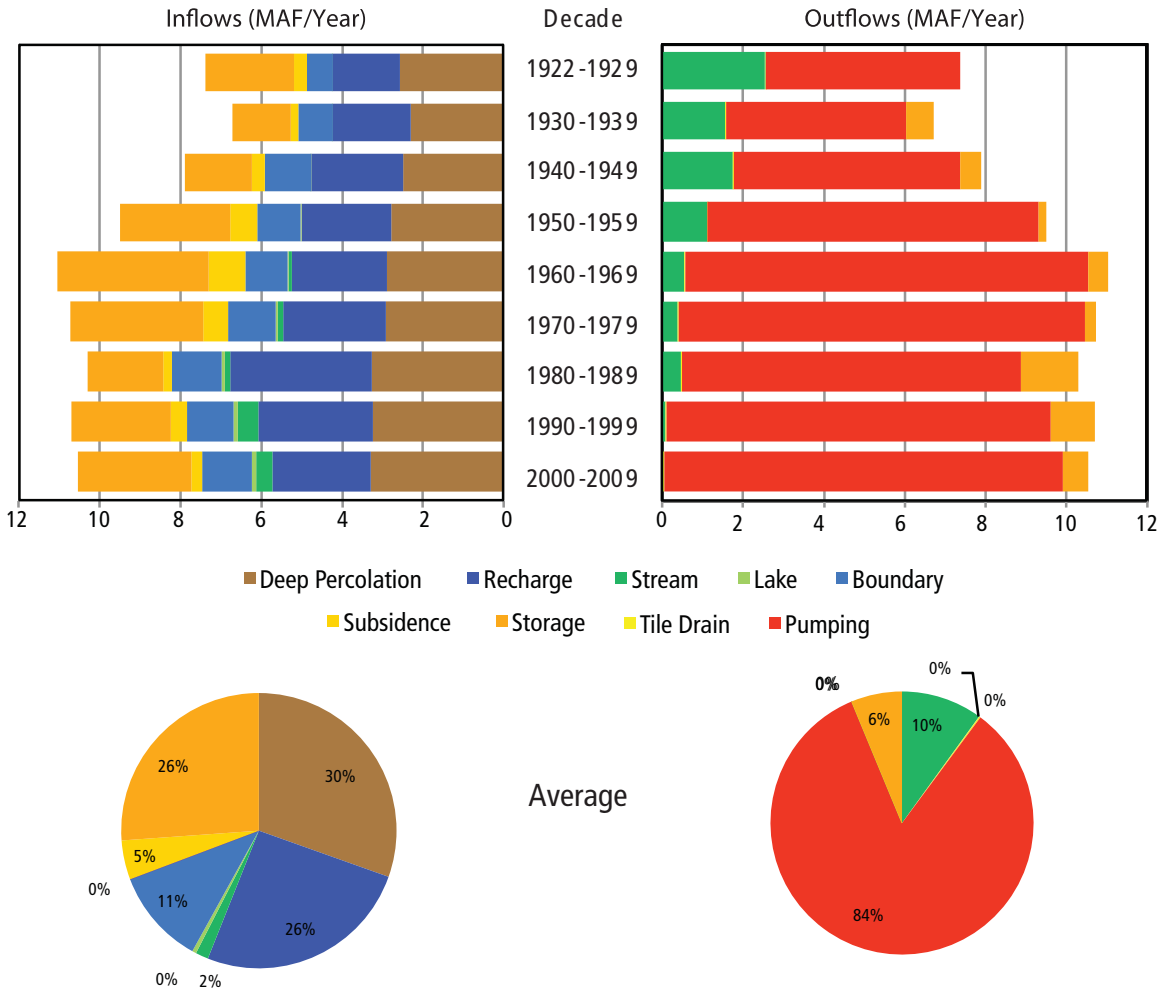
Figure 48. Simulated river inflows and outflows within the Central Valley, 2000-2009.

Note: Flow rates near zero may not appear on these figures.

Groundwater Flow System Water Balance

Central Valley aquifers receive water through deep percolation from the land surface, seepage from rivers and lakes, recharge through diversion canal losses and subsurface inflow from surrounding small watersheds, and lose water to seepage into rivers and lakes, flow to on-farm tile drains and to groundwater pumping (Figure 49). The total flow in and out of the groundwater flow system has increased significantly between the 1920s and 2000s due to the large increase in groundwater pumping over this period. Inflows from recharge and deep percolation also increased as a result of land

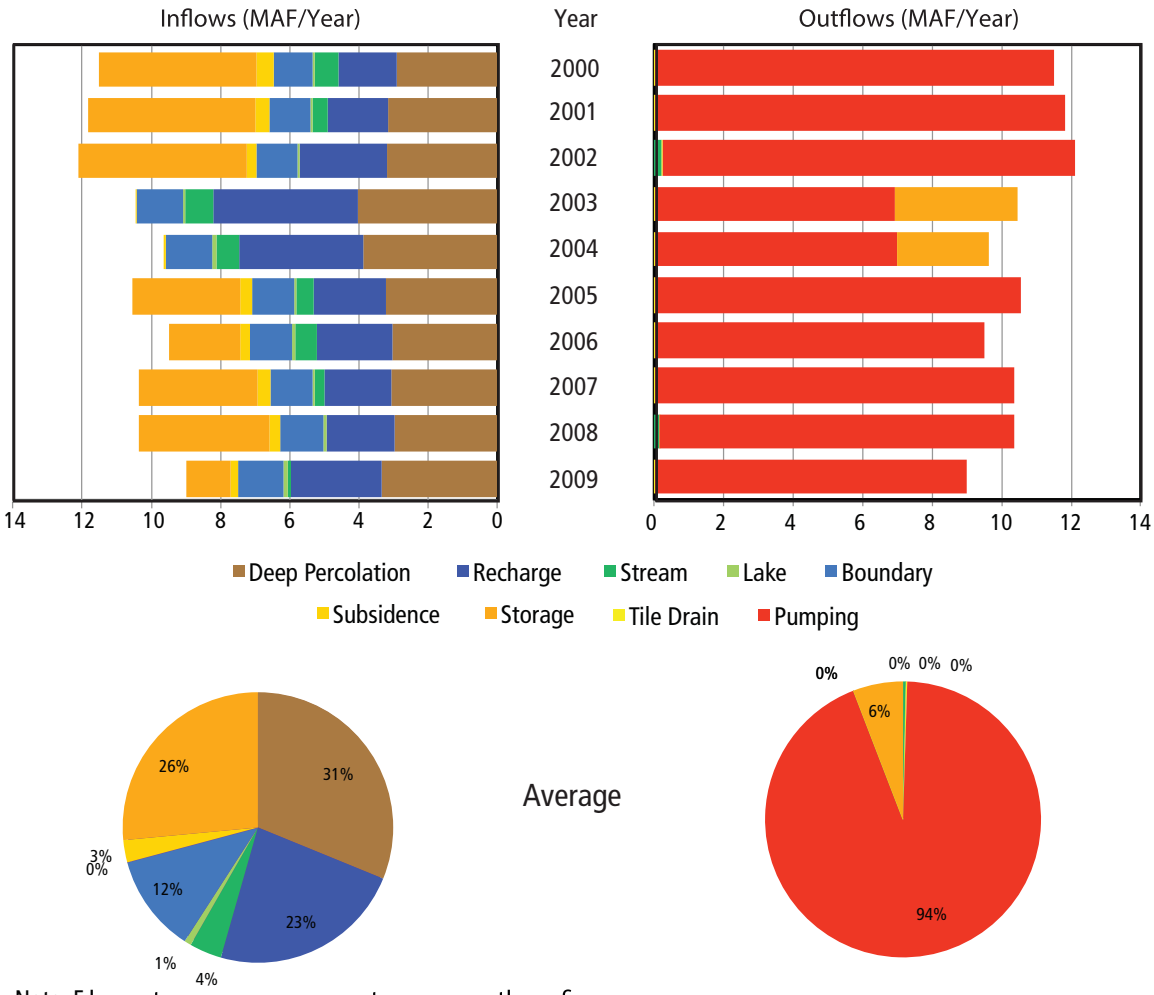
Figure 49. Groundwater process budget for the Central Valley for each decade, 1922-2009.



Note: Flow rates near zero may not appear on these figures.

use conversions from rain-fed native vegetation to irrigated agricultural crops. Over the long term, the increased groundwater pumping resulted in reduced groundwater levels, groundwater storage and groundwater discharges to rivers, and in some areas to subsidence of the land surface. A closer look at annual groundwater budgets for the Central Valley for water years 2000-2009 (Figure 50) shows that the inflows and outflows fluctuate significantly from year to year, driven mainly by changes in groundwater pumping. Groundwater storage was reduced (shown as inflows from storage on the figure) in 8 of the 10 years, rebounding slightly in 2003 and 2004 when deep percolation and recharge were high and pumping demands were low.

Figure 50. Groundwater process budget for California's Central Valley for each year, 2000-2009.

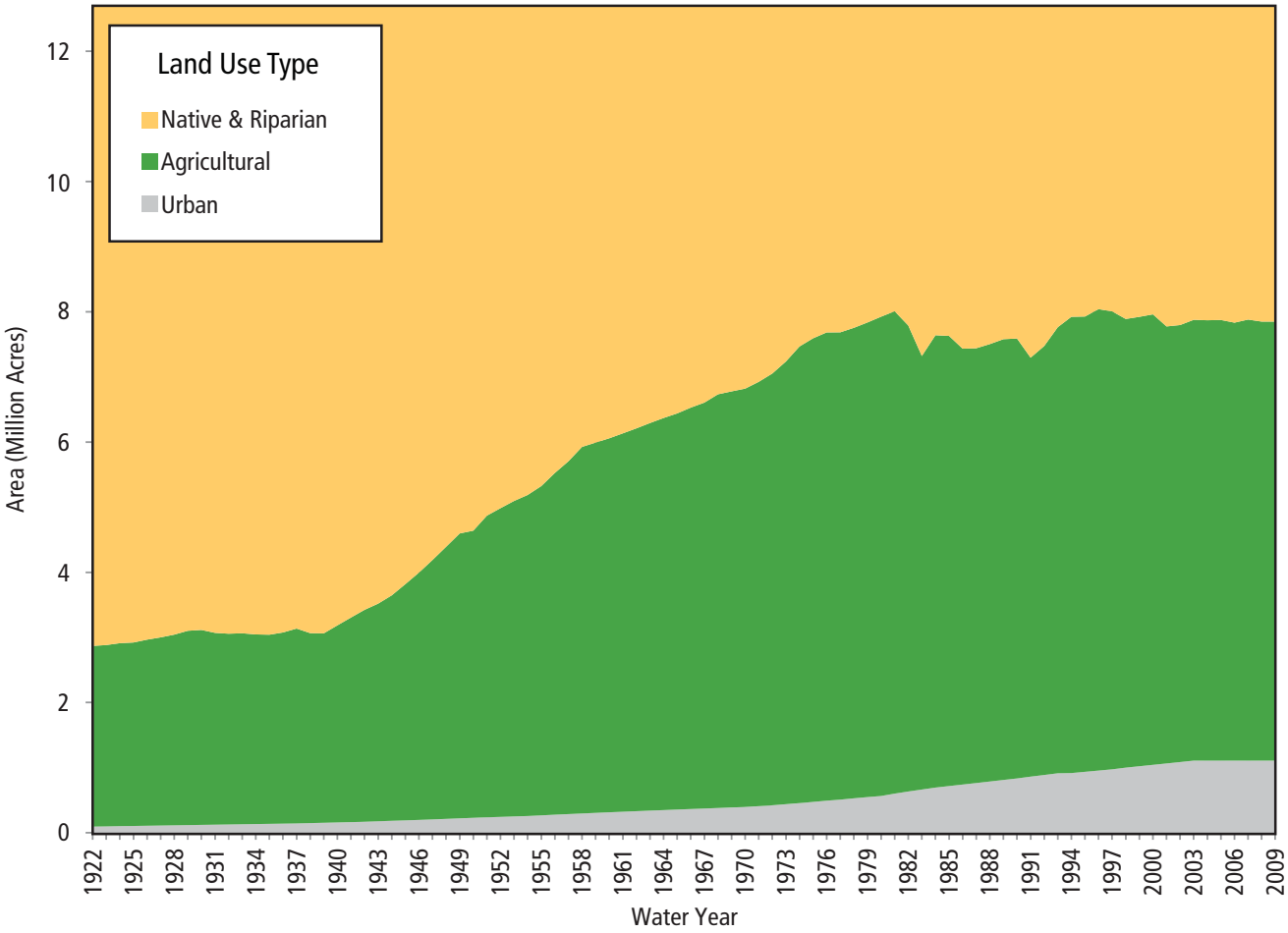


Note: F low rates near zero may not appear on these figures..

Land Use Changes

Changes in water use in California's Central Valley have been driven by changes in land use. Conversion of lands from native vegetation to agricultural and urban uses proceeded slowly from 1922 to approximately 1940, increased rapidly through the late 1950s and then less rapidly through the late1970s, and then leveled off (Figure 51). The land area occupied by native vegetation declined from 9.8 million acres in 1922 to less than 5 million acres by 1980, a reduction from 75% of the Central Valley land area in 1922 to 38% by 1980. Most of this land was converted to agriculture, which increased from 2.8 million acres in 1922 to 7.4 million acres by 1980, then declined to 6.7 million acres by 2009, an increase from 22% of the land area in 1922 to 58% in 1980 before falling to 53% in 2009. Urbanization proceeded slowly until the 1970s, then at a more rapid pace as some agricultural lands were urbanized. The urban area increased from less than 100,000 acres in 1922 to more than 500,000 acres in 1980 and more than 1.1 million acres in 2009, rising from 1% of the land area in 1922 to 4% in 1980 and 9% in 2009.

Figure 51. Historical land use changes in California's Central Valley.



The distribution of agricultural, urban and native vegetation land varies throughout the Central Valley (Figure 52). In the Sacramento River Basin, the agricultural land density is greatest in the area near the Sutter Buttes (model subregions 3 through 5), and urban lands are concentrated in the Redding Basin and Sacramento area (subregions 1 and 8). More than half of the land in the San Joaquin River Basin is in agriculture, with some urban land on the east (subregions 11 and 12). The agricultural land density is high in the northern half and southeastern corner of the Tulare Basin, with some urban lands in the northeastern and southeastern corners (subregions 16 and 21).

Figure 52A. Subregion agricultural area, 2000-2009.

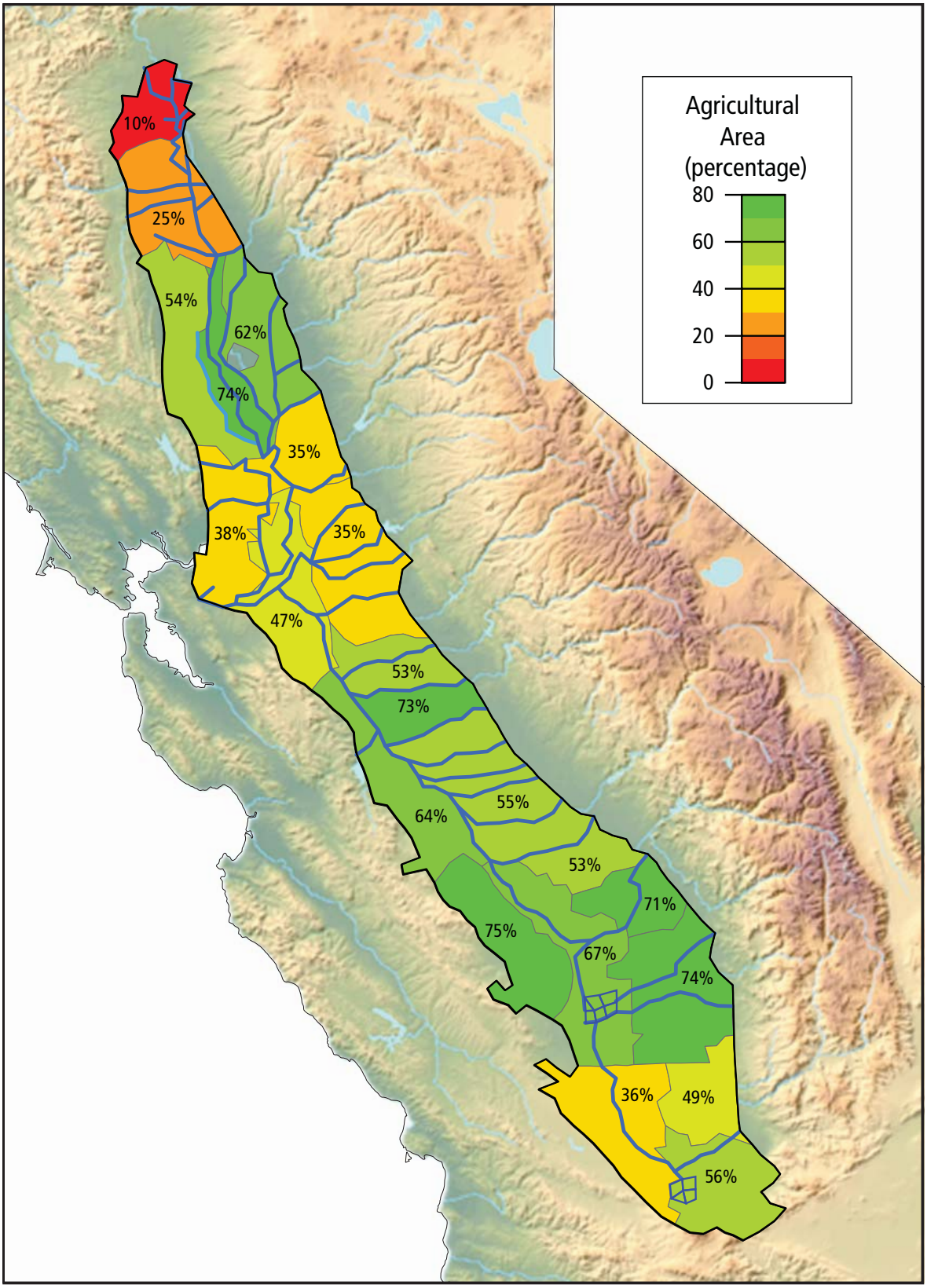
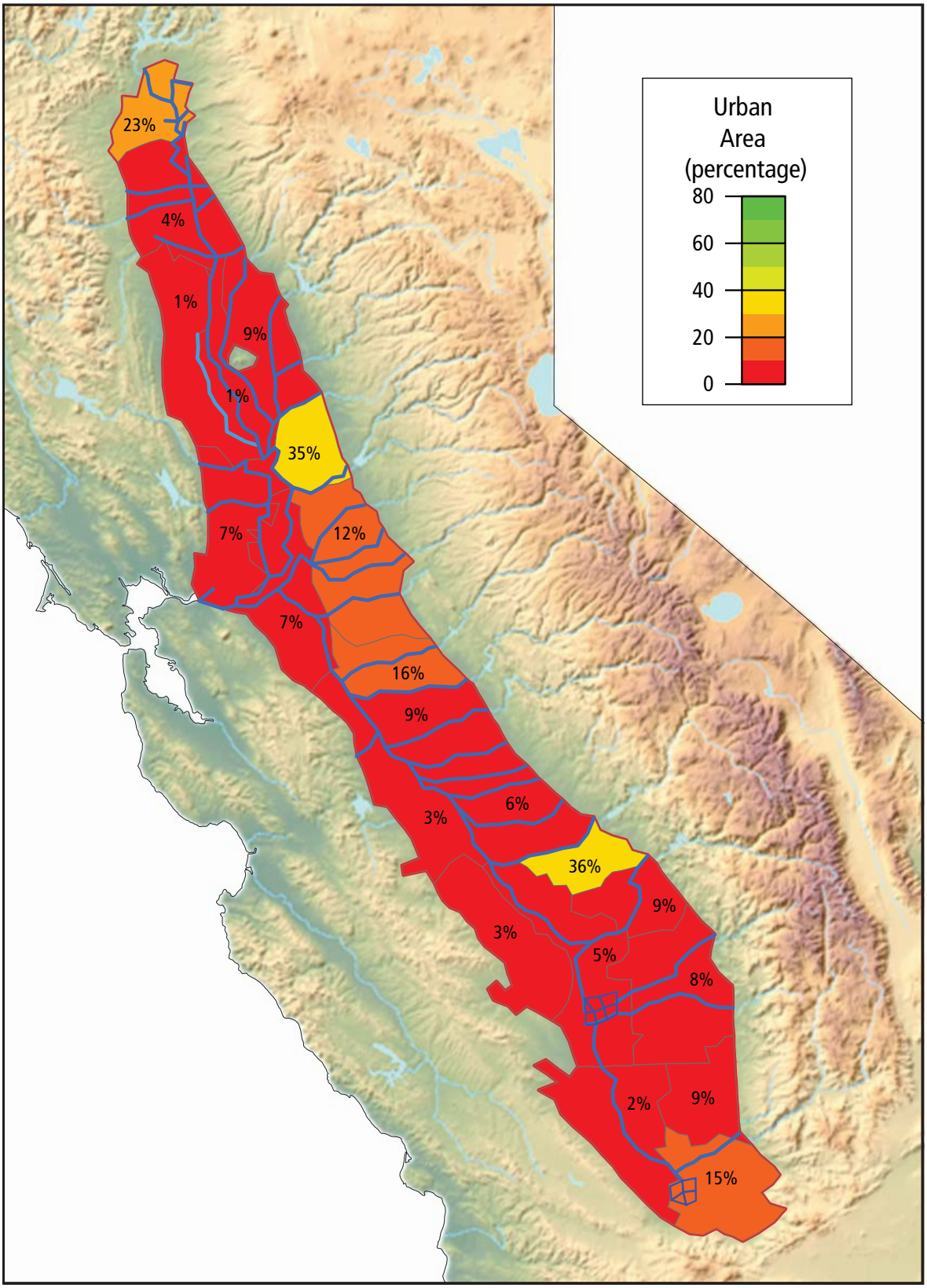
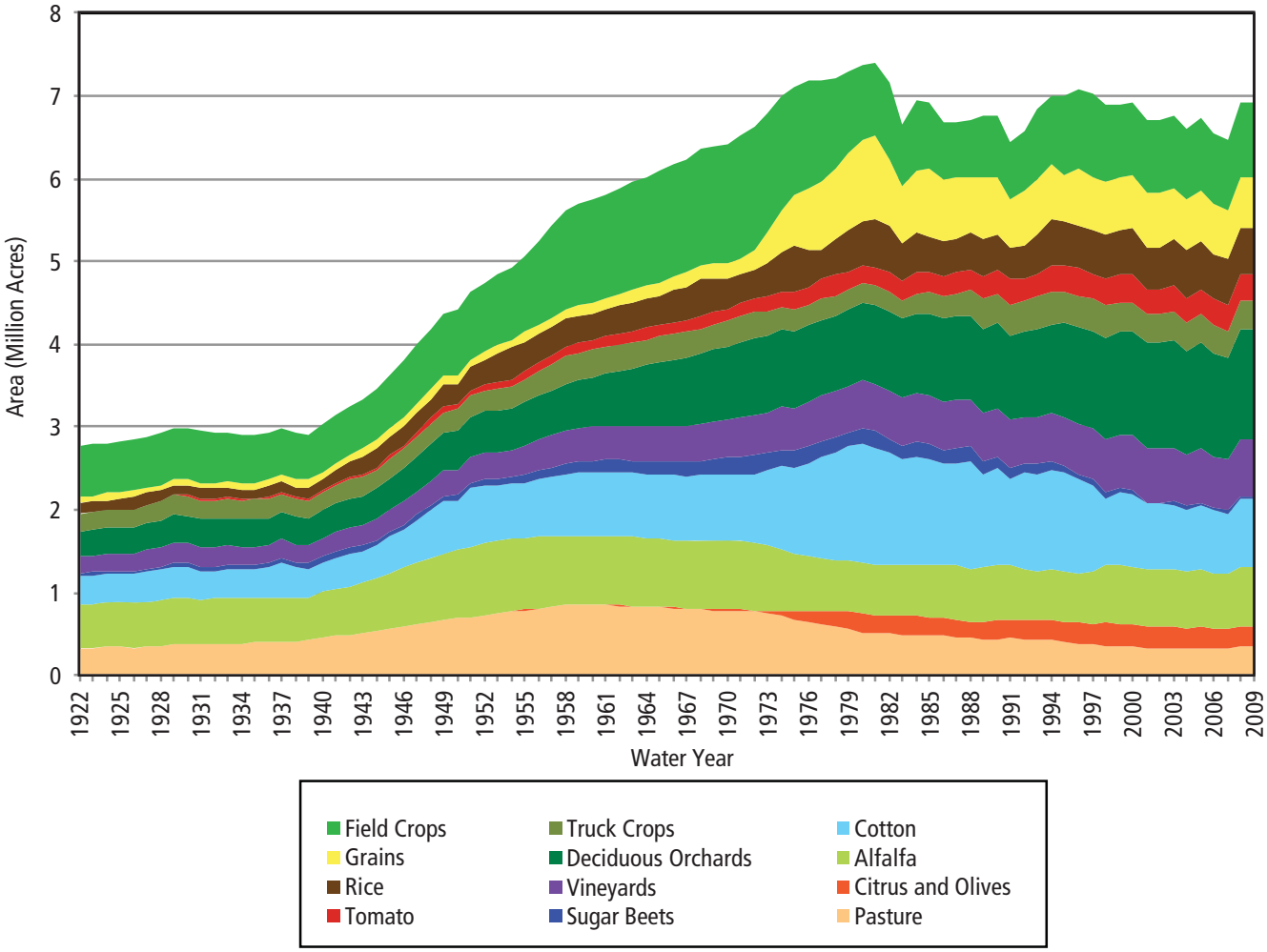


Figure 52B. Subregion urban area, 2000-2009.



The agricultural crop mix in the Central Valley has changed through time (Figure 53). The crop mix remained relatively stable as agriculture expanded from the 1920s to the 1970s, with the dominant crop types being field crops, cotton, alfalfa and pasture, and some expansion of rice, deciduous orchards and vineyards. The crop mix changed significantly between the 1970s and 2000s. The total agricultural acreage declined slightly as the acreages of grains, tomatoes, vineyards, deciduous orchards and subtropical orchards (citrus and olives) expanded and the acreage of field crops, cotton and pasture declined.

Figure 53. Historical Central Valley crop areas, 1922-2009.



Individual Flow Components

The detailed output files of the C2VSim model provide an in-depth look at how each of the components of the Central Valley hydrologic system changed between the 1920s and 2000s. Summaries by subregion and hydrologic region highlight regional differences in water demands and availability, and how these have affected the rivers and the groundwater flow system.

Precipitation

The total precipitation volume on the Central Valley floor fluctuates significantly from year to year (Figure 54). Precipitation rates are greatest in the north (Figure 6), with average annual precipitation between 2000 and 2009 ranging from 2.4 ft in the north to 0.5 ft in the south (Figure 55). Nearly half of the precipitation falling on the valley floor occurs in the Sacramento River Basin hydrologic region, which accounts for only 29% of the land area (Table 1). On the Central Valley floor, most precipitation falls in the winter months.

Figure 54. Historical annual precipitation volumes for California's Central Valley, 1922-2009.

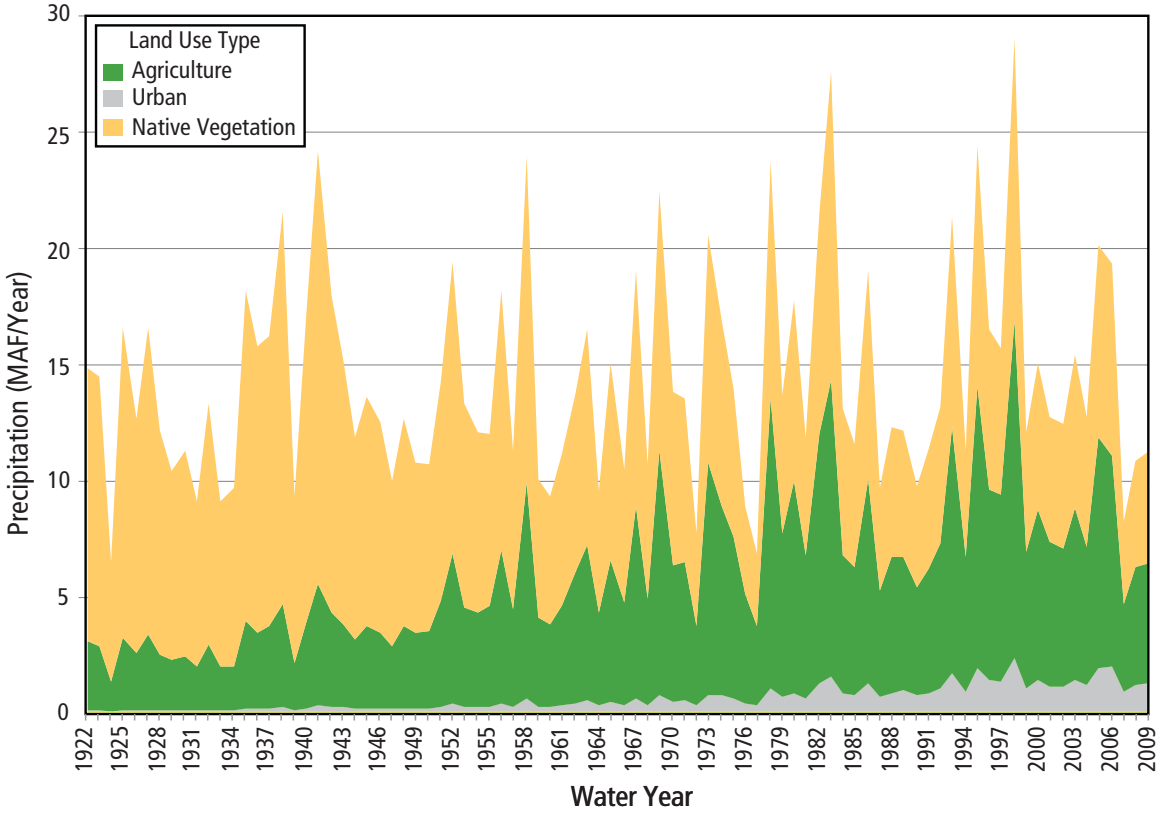
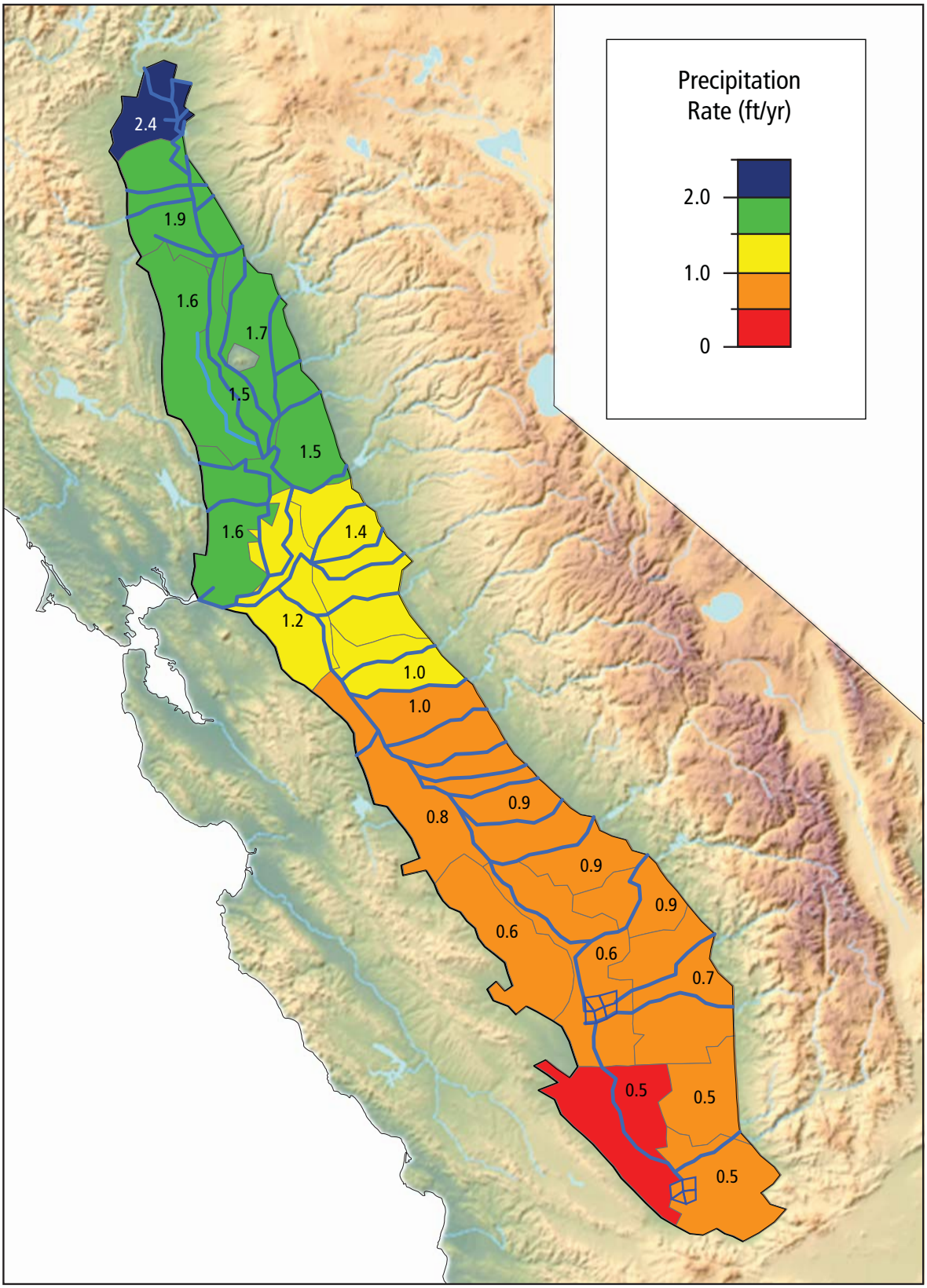


Figure 55. Average annual precipitation rate, 2000-2009.



Evapotranspiration

Simulated annual actual evapotranspiration increased by around 50% between the early 1920s and late 1970s, and then declined slightly through the 2000s (Figure 56). This increase was driven by land use conversion from rain-fed native vegetation to irrigated agriculture. In the 1920's, when agriculture occupied only 22% of the Central Valley land area, water consumption was evenly divided between agriculture and native vegetation (Figure 57). By the 1960s, when agriculture occupied 45% of the land area, agricultural evapotranspiration had increased to 75% of the total water consumption (Figure 57), where it remained through the 2000s. The winter evapotranspiration volume remained fairly constant while the summer evapotranspiration rose significantly between the 1920s and 1970s and then remained fairly constant through the 2000s (Figure 58). The urban share of total evapotranspiration increased from about 1% in the 1920s to 6% in the 2000s. Subregional annual evapotranspiration rates are generally proportional to the amount of developed area (Figure 59).

Figure 56. Historical simulated evapotranspiration in California's Central Valley, 1922-2009.

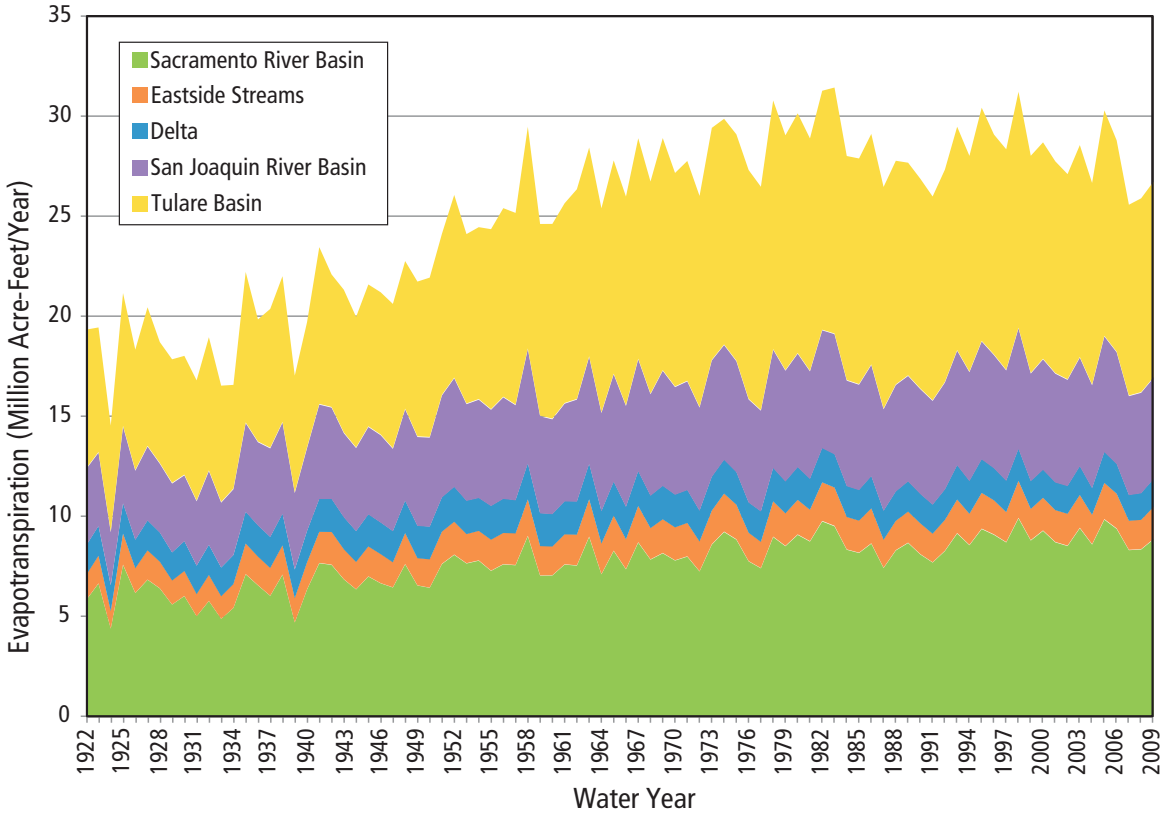


Figure 57. Share of total evapotranspiration to each land use type.

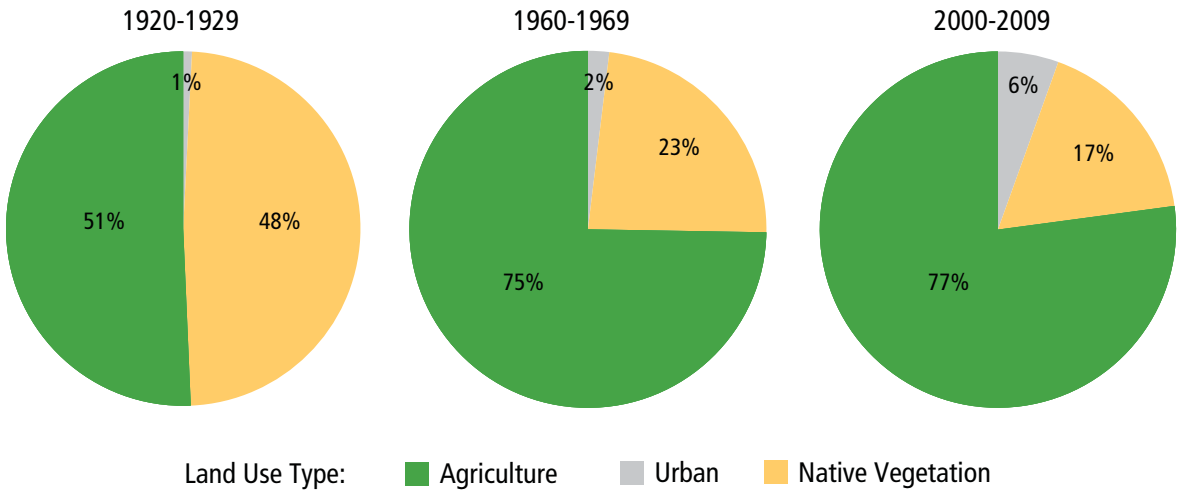


Figure 58. Average monthly evapotranspiration for each decade.

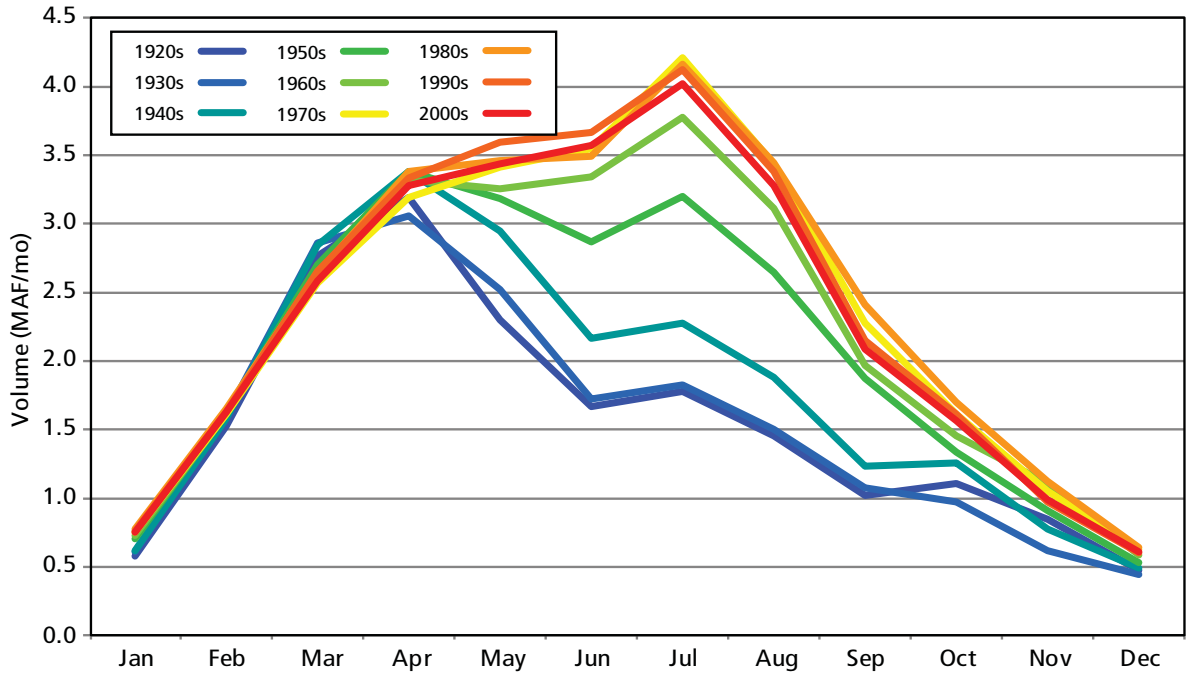
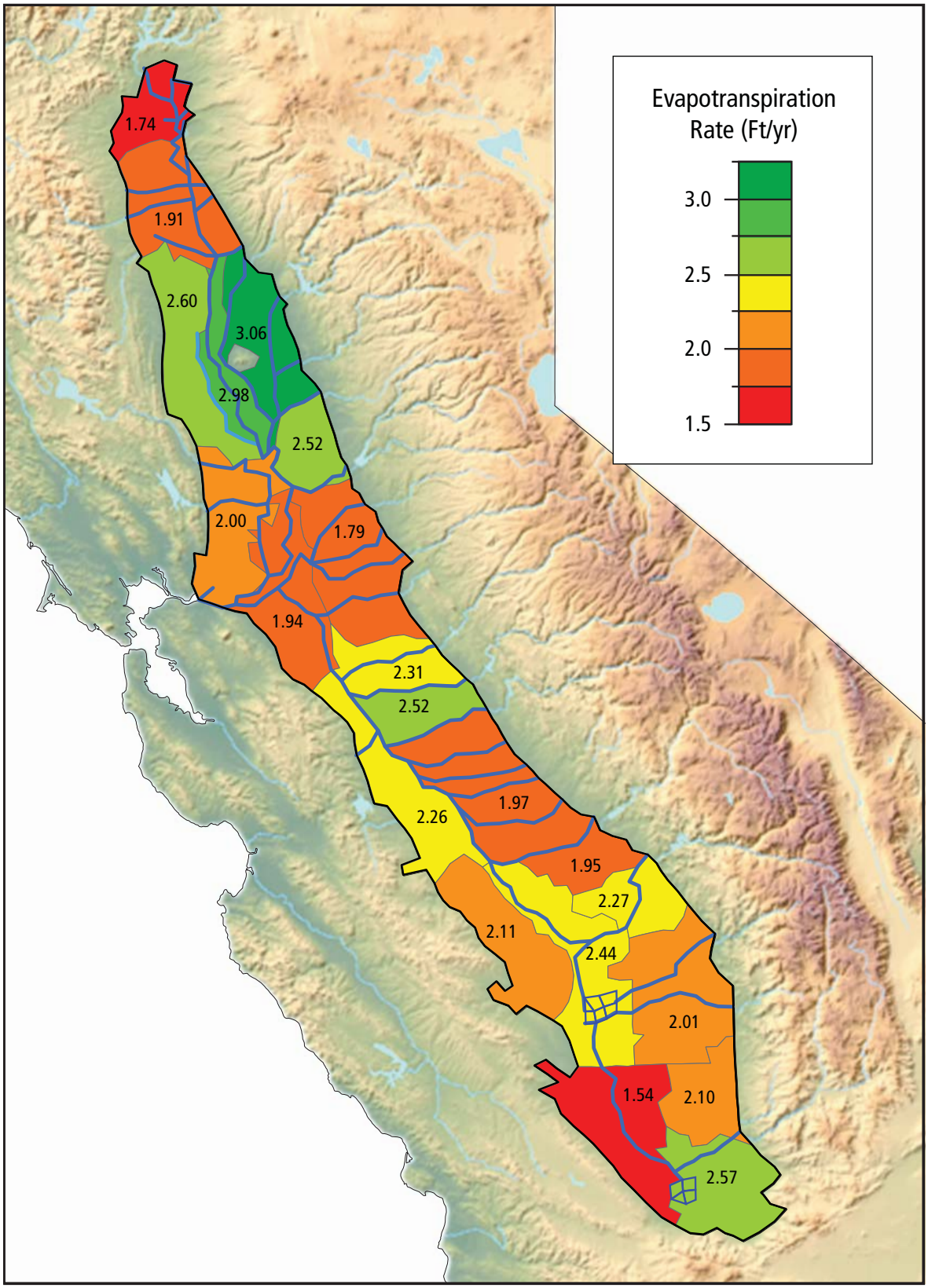


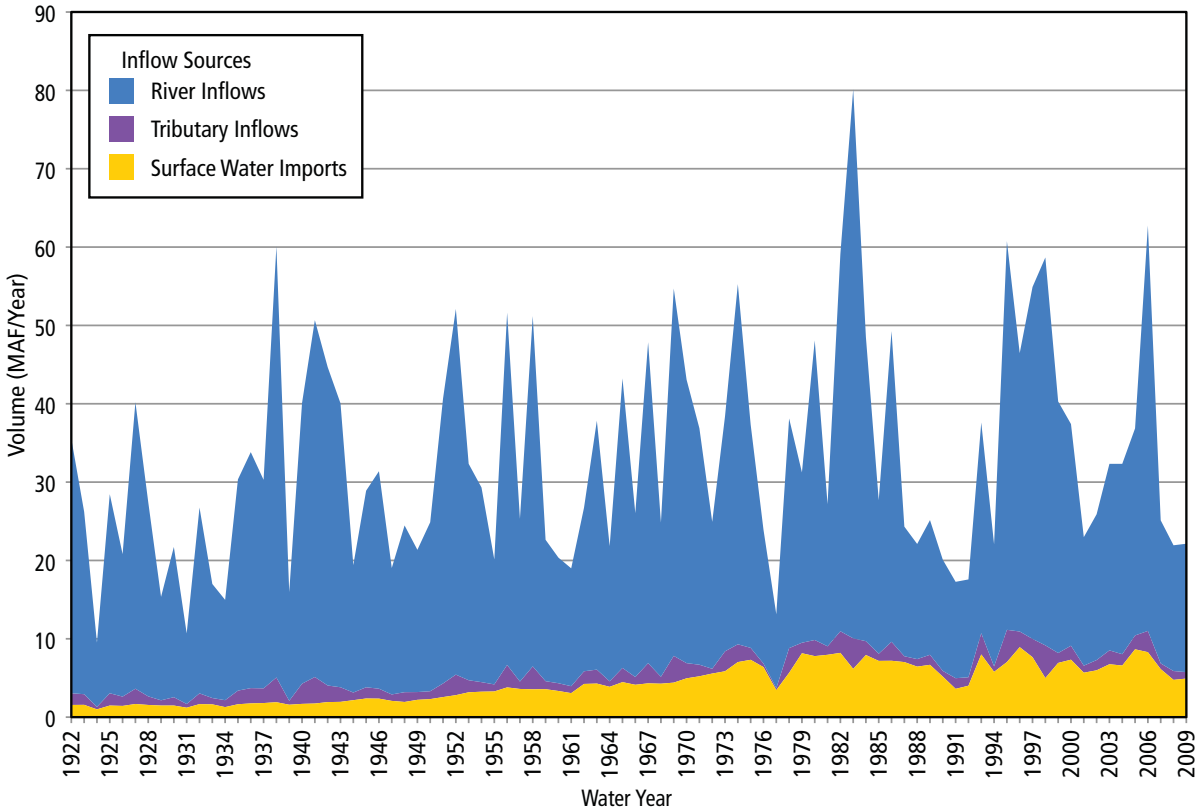
Figure 59. Simulated annual evapotranspiration rate, 2000-2009.



Surface Water Inflows

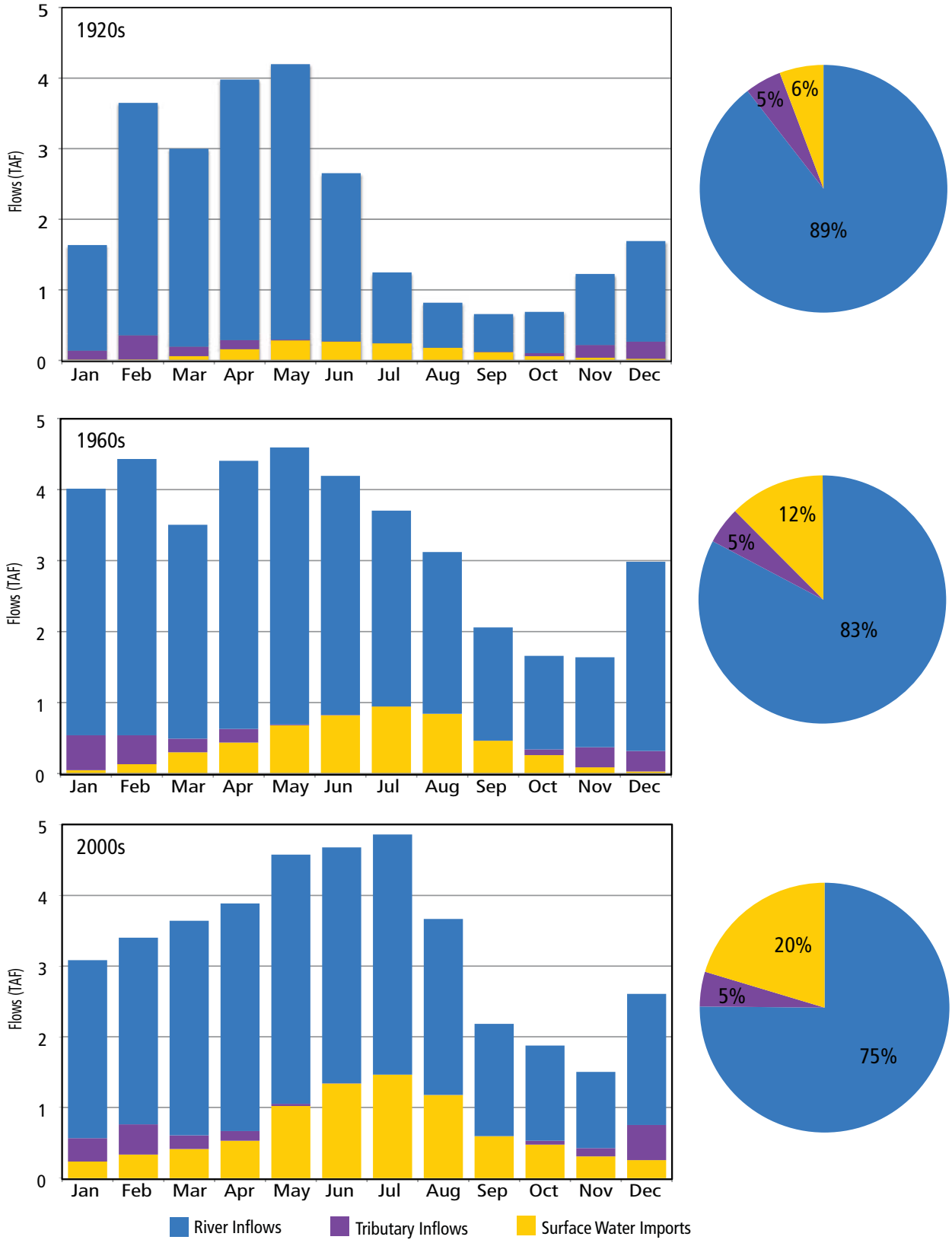
In the C2VSim model, surface water inflows are divided into three categories: river inflows, tributary inflows and surface water imports. The model contains detailed databases of historical monthly river inflow values and historical surface water diversions, and calculates surface water inflow from small ungauged tributary watersheds at run-time. River inflows occur on 36 rivers (Figure 17). Surface water imports are deliveries that occur through canals that are not explicitly simulated, including the Friant-Kern Canal, the California Aqueduct, and many smaller canals (Figure 17). Tributary inflows are dynamically calculated as the outflow from 210 small-stream watersheds (Figure 12). Total surface water inflows (from river inflows, surface water imports and tributaries) fluctuate significantly from year to year (Figure 60), and averaged 33 MAF/yr from 1922 to 2009. The lowest inflow of 10 MAF occurred in 1924, a low-precipitation year when few reservoirs existed, and the greatest inflow of 80 MAF occurred in 1983, a year with extremely high precipitation in the Central Valley watershed. Tributary inflows have supplied a small but steady inflow, and the portion occurring as imports has steadily increased. The greatest annual fluctuations occur in river inflows, which generally reflect the variability of precipitation in upstream watersheds. Annual surface water inflows to the Central Valley were above 20 MAF/yr for most years after 1945 owing to the presence of reservoirs that allow carry-over of water from one year to the next.

Figure 60. Sources of surface water inflows to the Central Valley, 1922-2009.



Average monthly inflows for three decades (1920s, 1960s and 2000s) demonstrate how the construction of regulating reservoirs has affected the annual distribution of river flows (Figure 61). In the 1920s, surface water inflows were high from February through May and dropped steeply to very low levels by August. Only 6% of the surface water inflows were imports. By the 1960s, the expanded reservoir capacity allowed high surface water inflows to be maintained through June, with a more moderate decline through October. By the 2000s, the construction of additional reservoirs allowed the timing of surface water inflows to be further shifted so they increased from December through July, and then tapered off through September. During this period, the portion of surface water inflows entering the Central Valley via river channels declined from 89% in the 1920s to 83% in the 1960s and 75% in the 2000s, and the proportion entering via canals (as surface water imports) increased from 6% in the 1920s to 12% in the 1960s and 20% in the 2000s. The portion entering as tributary inflows remained constant at 5%. The Central Valley hydrologic system was also significantly impacted as the timing of the surface water inflows shifted from the winter months to the late spring and summer, and the flow regime in the rivers changed from one characterized by periods of high and low flows to one characterized by steady, moderate flows.

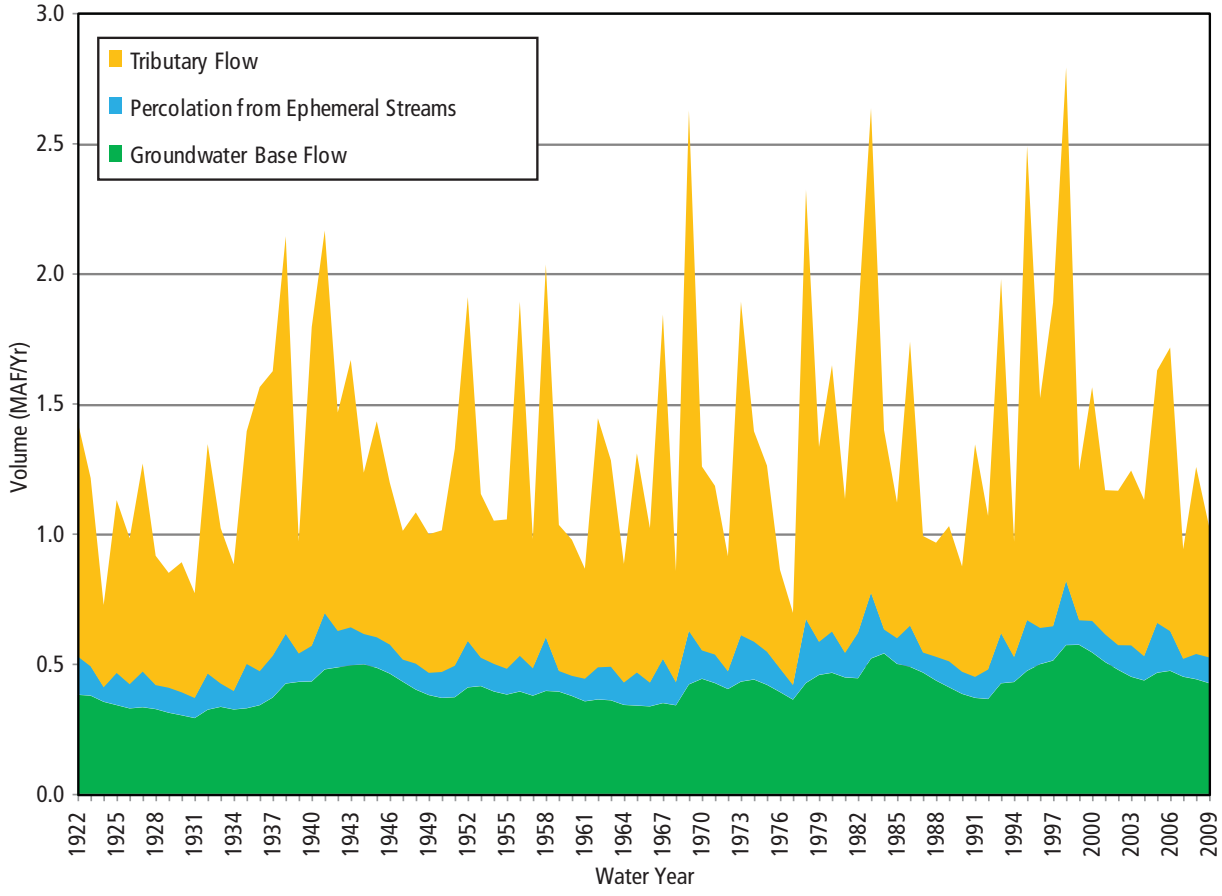
Figure 61. Sources of inflows to California's Central Valley.



Small-Stream Watersheds

The Central Valley is bordered by many small watersheds (shown in Figure 12), which are simulated in C2VSim using the IWFM Small-Stream Watershed Process. These areas are generally characterized by small or intermittent streams which do not have extensive flow records. These areas contribute about 5% of the inflows to the Central Valley as groundwater base flow and surface water. Some of the water that enters the Central Valley in these intermittent stream channels percolates through the stream beds to the groundwater aquifer, and the remainder flows into the river system as *Tributary flow*. Annual groundwater base flow, percolation from intermittent streams and tributary flow are summarized in Figure 62. Recharge from intermittent streams and tributary flow to rivers follow the precipitation pattern, and can vary significantly from year to year. Groundwater base flow, which represents lateral discharges from the aquifer underlying the small-stream watershed, fluctuates gradually, rising after several wet years and falling after several dry years.

Figure 62. Historical Central Valley inflows from small-stream watersheds.

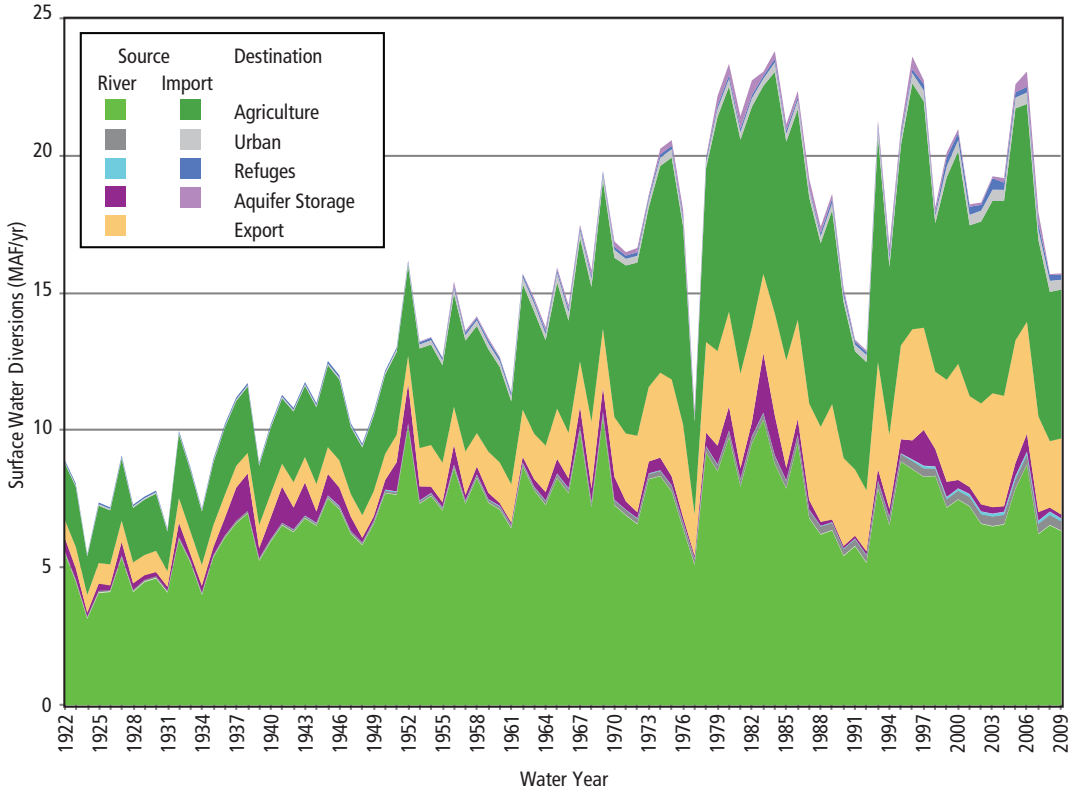


Surface Water Deliveries

The annual surface water delivery volume increased steadily from approximately 5-8 MAF/yr in the 1920s to 17-20 MAF/yr in the early 1980s (Figure 63). This diversion volume includes irrigation return flows that are re-diverted at points downstream. This steady increase occurred even during dry periods, as reservoirs were constructed on the major rivers flowing into the Central Valley. The only notable exception to this steady increase occurred in 1977 during a drought, when surface water deliveries dropped to around 11 MAF/yr. This steady increase stopped abruptly in the mid-1980s. Between 1984 and 1992, the annual surface water delivery volume fell by nearly half as the state experienced an extended dry period, and between 1993 and 2009 annual deliveries fluctuated significantly, rising in wet periods and falling in dry periods.

The portion of surface water deliveries entering the Central Valley through canals (*Imports*) increased from around 30% in the 1920s to nearly 50% in the 1970s, and remained at approximately this level through 2009. This reflects the construction of large dams and associated distribution canals, including the California Aqueduct, Friant-Kern Canal and Madera Canal, and the construction of regulating reservoirs in older distribution systems such as the Modesto Irrigation District and Tuolumne Irrigation District. Meanwhile, the volume of diversions coming directly from rivers within the Central Valley approximately doubled from 4-5 MAF/yr in the 1920s to 6-12 MAF/yr by the 1980s, with significant declines in dry periods.

Figure 63. Diversion volumes to each end-use in the Central Valley, 1922-2009.



The portion of surface water diversions going to agricultural users has declined from 94% in the 1920s to 90% in the 2000s (Figure 64), the portions going to urban users and wild-life refuges increased, and the portion going to aquifer storage and recovery has remained constant. A comparison of annual diversions for the 2000s shows that urban diversions remained fairly steady from year to year, agricultural diversions (which include diversions to wildlife refuges) fluctuate significantly from year to year, and a significant portion of these diversions became seepage, recharging the Central Valley aquifer (Figure 65). The model subregions that receive the greatest surface water diversion volumes are in the central Sacramento River Valley (subregions 3 and 5), on the west side of the San Joaquin Valley (subregions 10 and 14) and in the Kaweah River and Tule River watersheds (subregion 18) (Figure 66).

Figure 64. Destinations of surface water diversions.

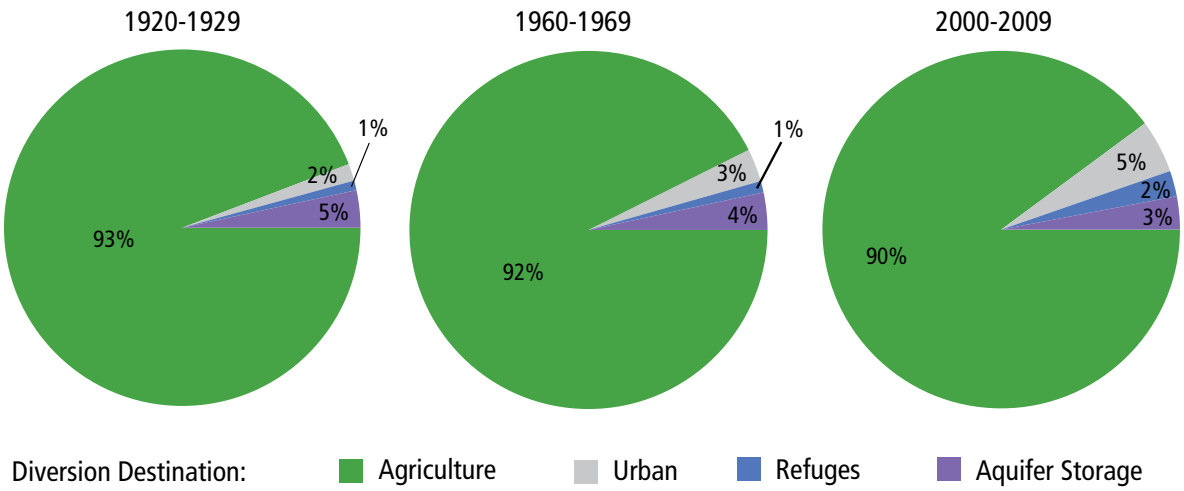


Figure 65. Simulated surface water destinations for California's Central Valley for water years 2000-2009.

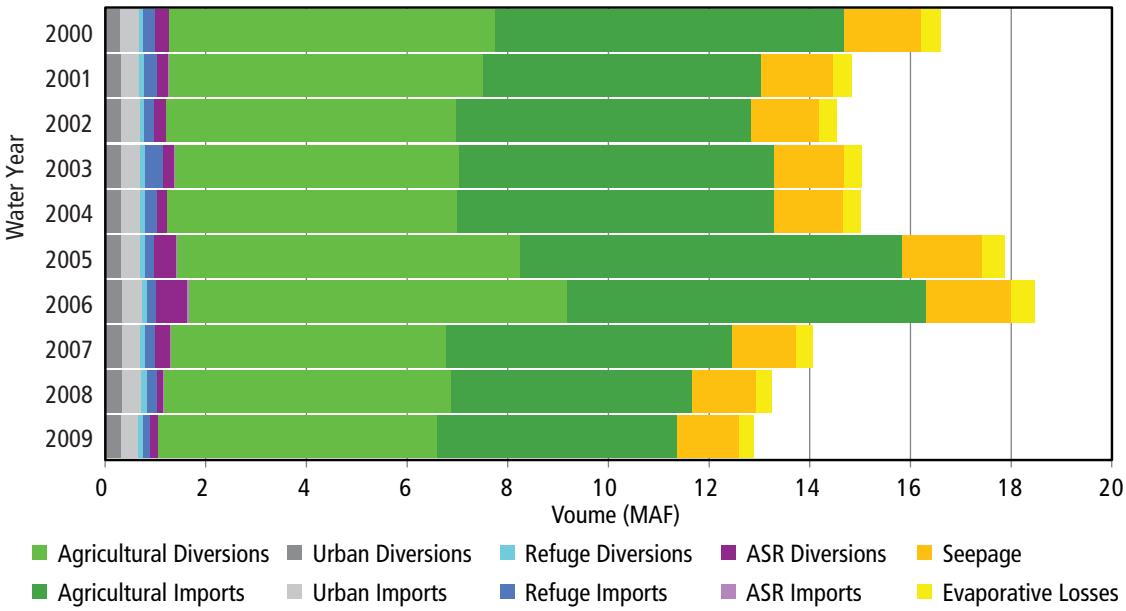
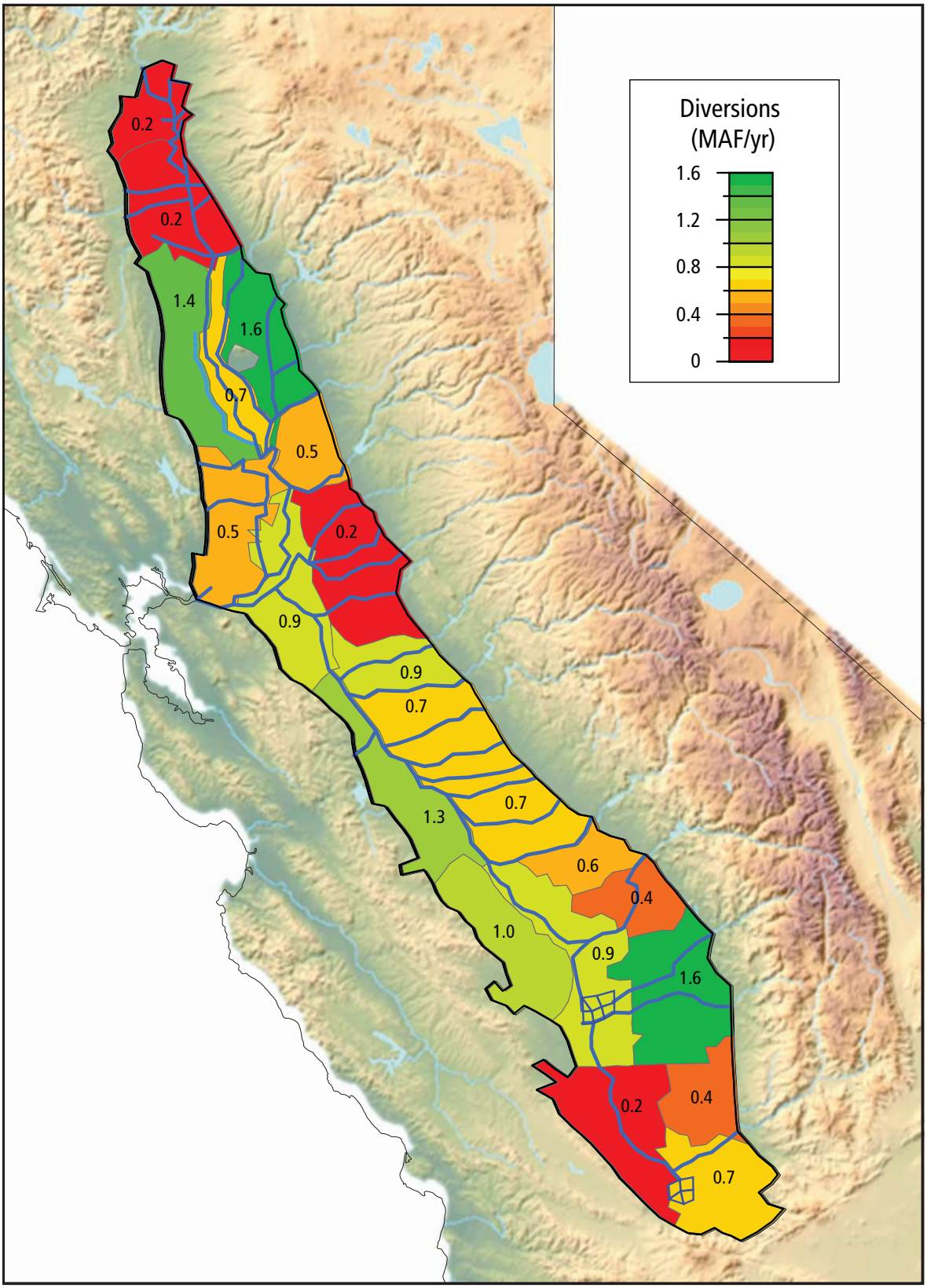
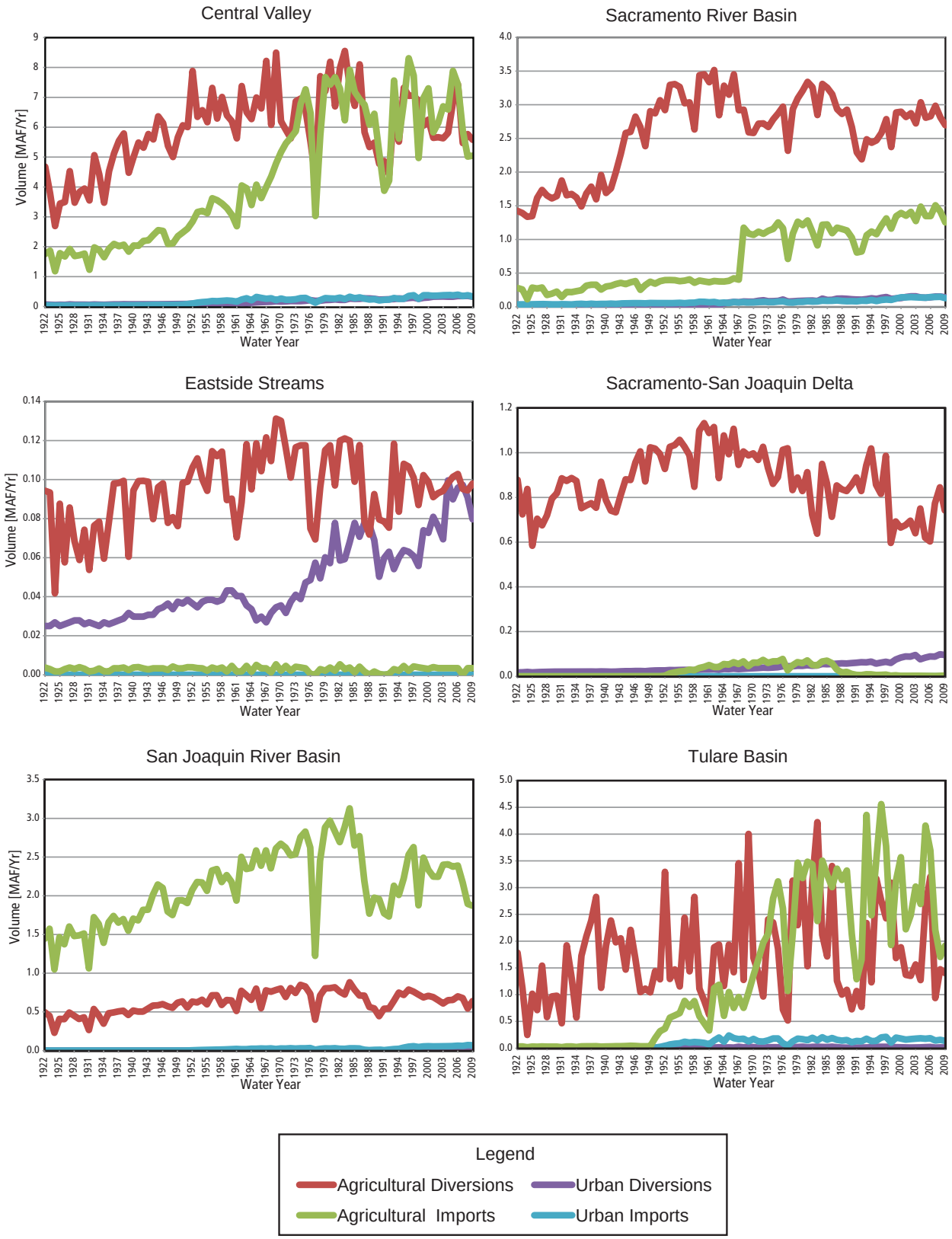


Figure 66. Average annual surface water supply volume, 2000-2009.



Surface water supplies have historically been more reliable north of the Sacramento-San Joaquin Delta (Figure 67). In the Sacramento River Valley, the total supply volume has increased through time, with an increase in imports beginning in the 1960s. In the Eastside Streams hydrologic region, the total supply volume increased, and urban use consumed approximately half of total deliveries by the 2000s. Surface water use in the San Joaquin River Valley increased steadily through the early 1980s, and then fell sharply as diversions from rivers declined significantly and imports remained fairly constant. Total diversions have steadily increased in the Tulare Basin, with imports increasing dramatically after 1950, but there are large fluctuations from year to year.

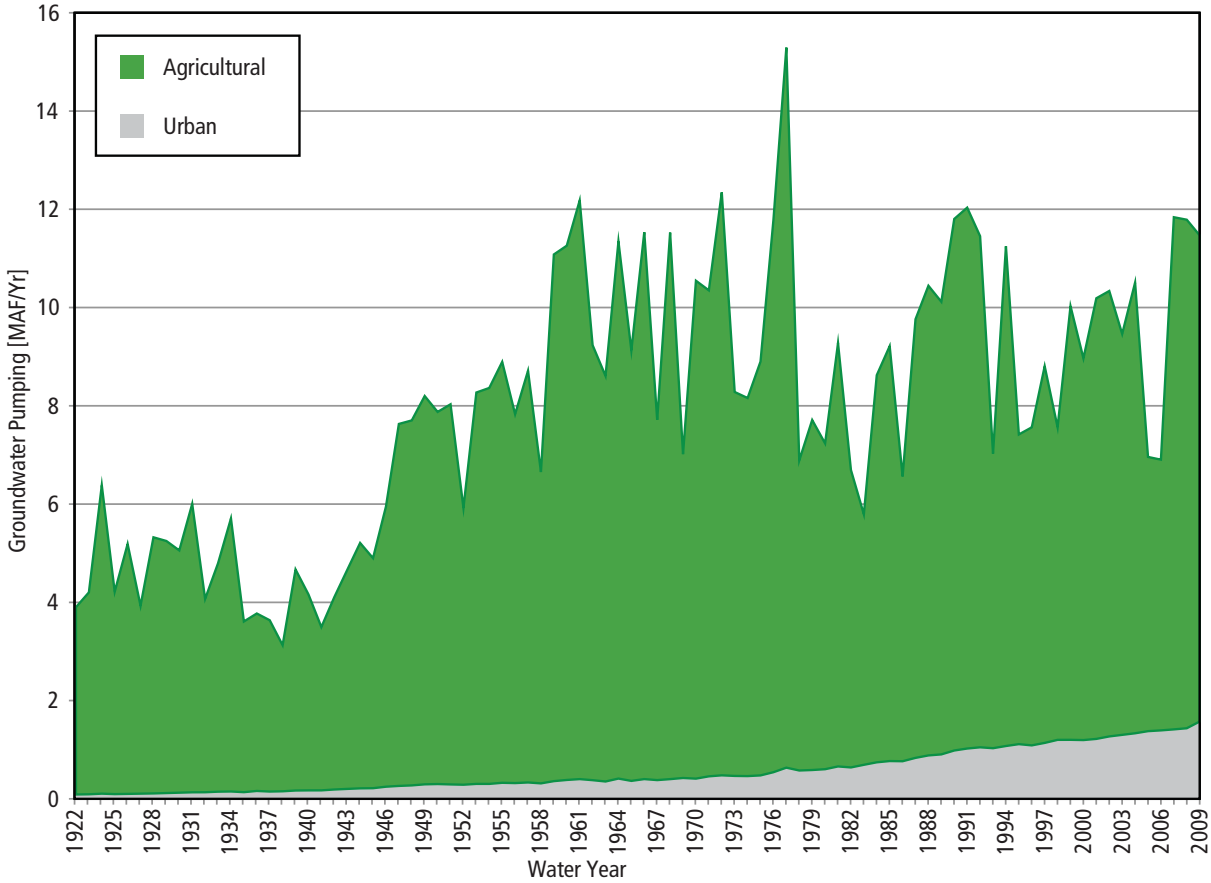
Figure 67. Agricultural and urban surface water sources for each hydrologic region, 1922-2009.



Groundwater Pumping

Groundwater serves as the main source of water for some agricultural areas and for many cities, and also as a supplemental water source in dry periods for some agricultural and urban users that generally rely on surface water. The C2VSim model calculates subregional groundwater pumping each month to meet agricultural and urban demands that are not met with surface water diversions. The greatest increase in groundwater pumping occurred between approximately 1940 and 1960, when the annual extraction rate tripled from around 4 MAF to almost 12 MAF (Figure 68). The development of several large surface water delivery projects around this time reduced the reliance on groundwater in wet years, and annual extraction rates fluctuated between approximately 7 and 12 MAF before rising above 15 MAF during the 1977 drought. Several management practices adopted after the 1977 drought, including changes in cropping practices, and expansion of conjunctive use and surface water exchanges, have reduced groundwater extraction below the levels of the 1960s in wet years; groundwater pumping has not risen above 12 MAF/yr since 1977. Simulated urban groundwater pumping increased from 544 TAF in 1999 to 740 TAF in 2009, a 36% increase in 10 years.

Figure 68. Simulated historical Central Valley groundwater pumping, 1922-2009.



Groundwater pumping rates vary seasonally, and the seasonal rates and patterns have changed since the 1920s, as shown in Figure 69. In the 1920's, agricultural pumping peaked at 0.8 MAF/mo in July and August, and there was very little urban pumping. In the 1960's, pumping rates over 1.8 MAF/mo occurred in May through June, with a small but steady urban pumping demand. In the 2000's, the maximum pumping rate of over 1.8 MAF/mo occurs only in May, and urban pumping is over 0.1 MAF/mo throughout the summer. Simulated agricultural pumping rates are very low to near zero from November through February, rise steeply through the spring to peak in July, and then fall sharply when the growing season ends. (The small groundwater pumping peak in October may be an artifact of the fact that crops are specified by water year in the model, with a shift in crops on October 1of each year, and a corresponding need to adjust soil moisture balances.)

Reliance on groundwater pumping also varies by hydrologic region and subregion (Figure 70). The simulated annual groundwater pumping volume has steadily increased in the Sacramento River Basin, and appears to be continuing to rise. The annual pumping rate rose steadily from the 1920s through the mid-1970s, then nearly doubled in 1977, the driest year in the simulation period. After 1977, the pumping rate fell to previous levels for over a decade, then increased significantly in the mid-1990s, and exceeded the 1977 value in three years between 1990 and 2009, suggesting an increasing reliance on groundwater. Although groundwater pumping rates in the Sacramento River Basin have historically been lower than the rates in other Central Valley regions, they appear to be rising steadily, especially in the Sacramento area.

Groundwater pumping rates have also risen steadily in the San Joaquin River Basin. The greatest simulated groundwater pumping rate occurred during the 1977 drought, when very little surface water was available. The groundwater pumping rate has continued to rise, but has not surpassed the 1977 rate, perhaps due to changes in cropping and water management practices. Simulated groundwater pumping rates in the Tulare Basin vary significantly from year to year in response to the availability of surface water (shown in Figure 67). Simulated average annual groundwater pumping rates are large for several of the Tulare Basin subregions, which have experienced persistent groundwater overdraft (DWR, 2003). A map of average annual groundwater pumping volumes for each model subregion (Figure 71) indicates the greatest pumping rates occur in Sacramento and San Joaquin counties (subregion 8), Merced and Madera counties (subregion 13), Kings County and part of Fresno County (subregion 15) and Kern County (subregions 19 and 21).

Figure 69. Simulated average monthly Central Valley groundwater pumping.

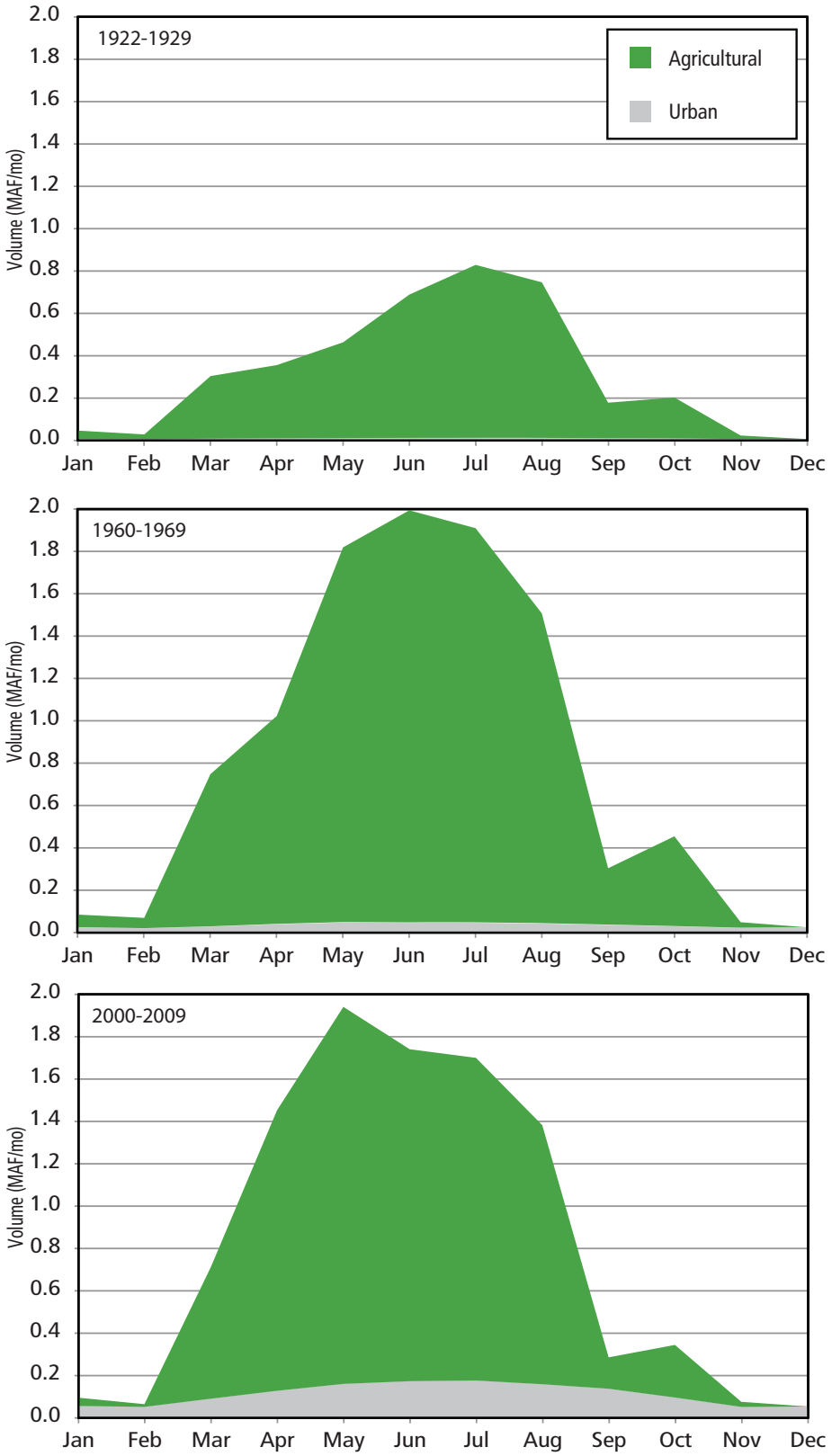


Figure 70. Simulated agricultural and urban groundwater pumping for each hydrologic region, 1922-2009.

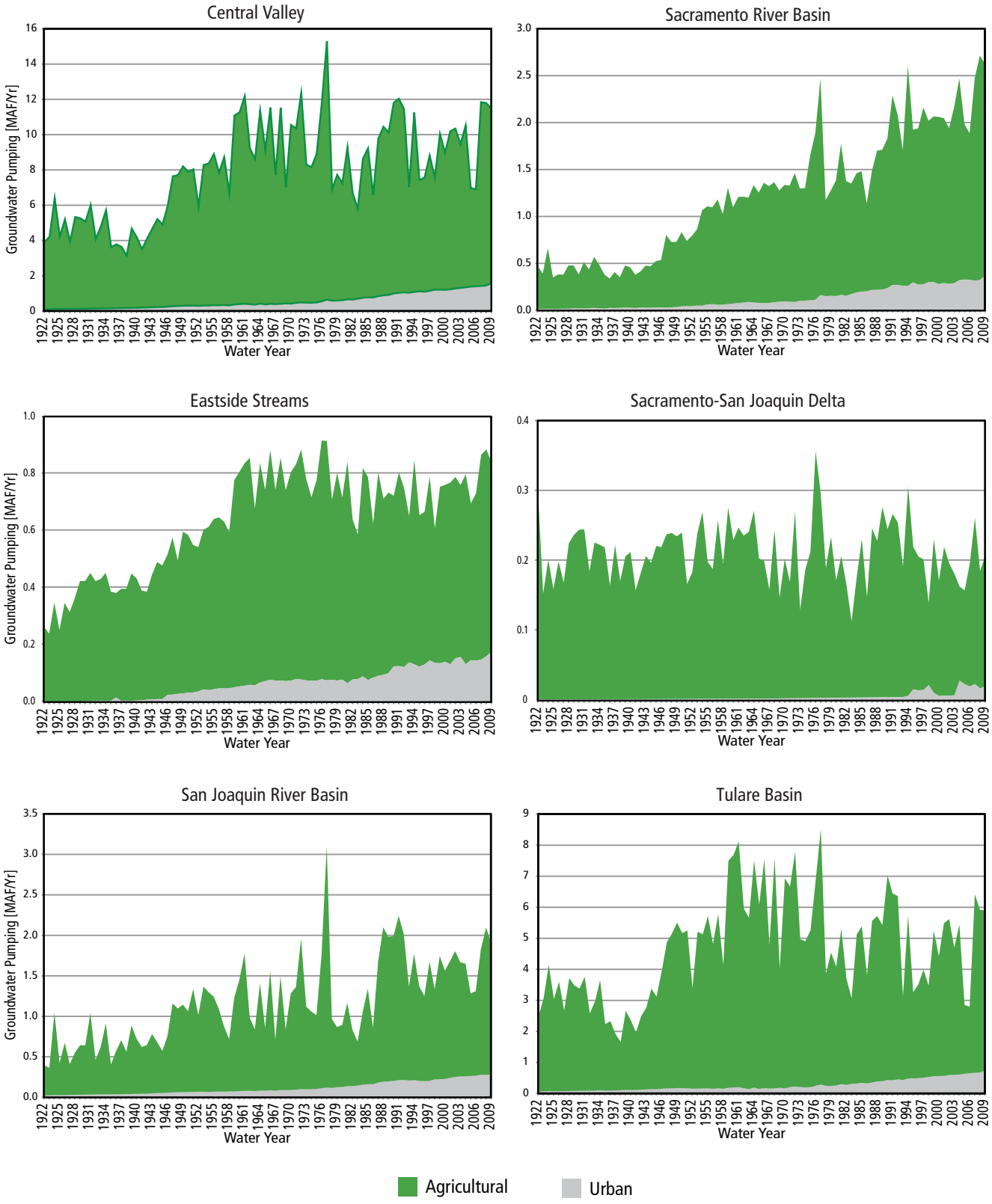
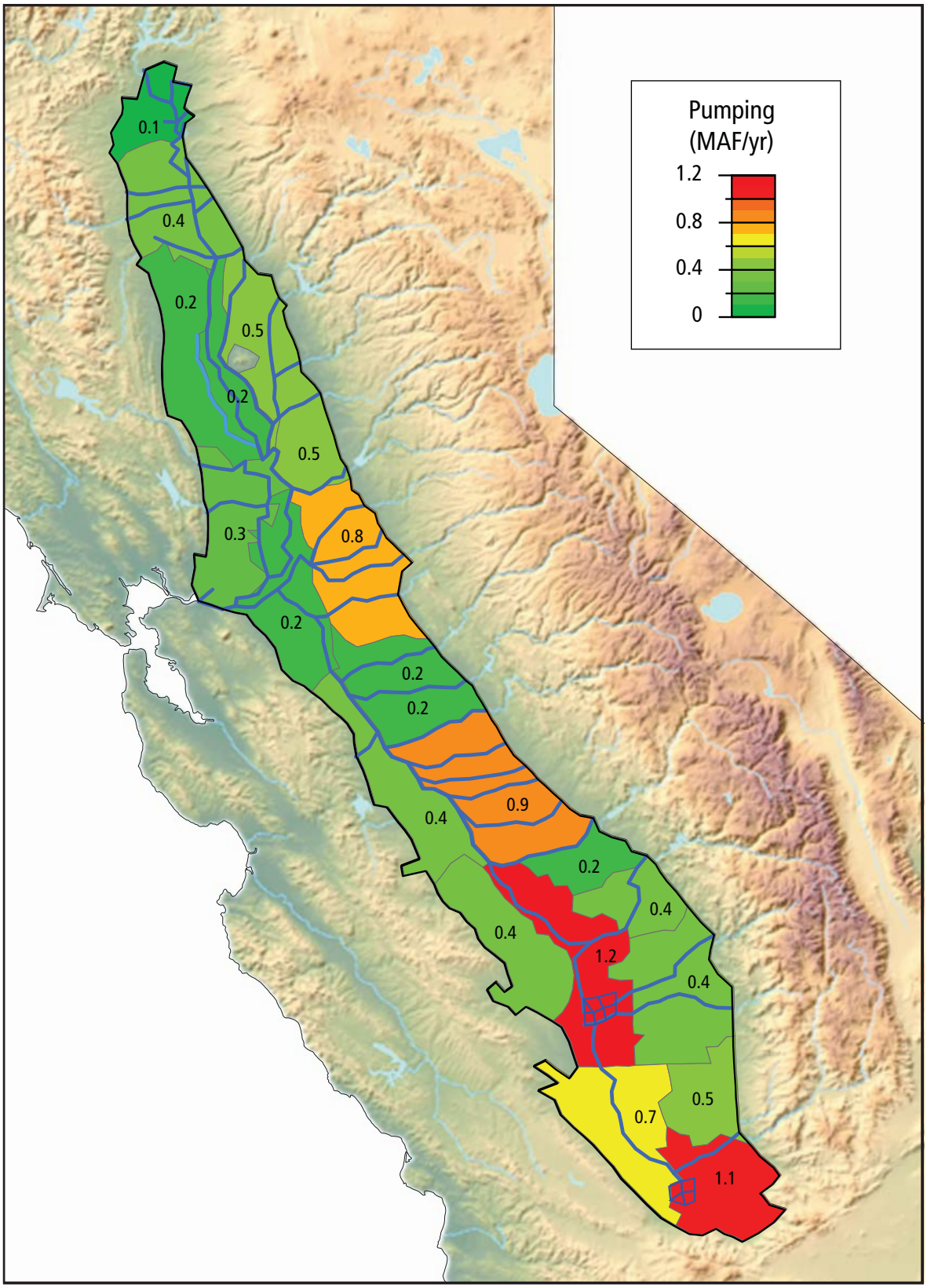


Figure 71. Simulated average groundwater pumping, 2000-2009.



Recharge and Deep Percolation

IWFM simulates several types of subsurface water flows from the land surface to the water table, which are classified as "Deep Percolation" and "Recharge", depending on the flow path. The downward flow of soil moisture from the root zone into the unsaturated zone is called "Deep Percolation", and the flow from the unsaturated zone to the water table is called "Net Deep Percolation". Water flows vertically through the unsaturated zone at a rate determined by the unsaturated vertical hydraulic conductivity. The unsaturated zone is simulated with two horizontal layers. This method is appropriate given the depth to the water table and the grid scale of the C2VSim model, which incorporates elements with a very large scale with respect to the flow processes being simulated (Gogolev, 2002).

In IWFM, "Recharge" is water flowing downward to the water table that is derived from three sources: irrigation canal seepage, bypass seepage, and aquifer storage programs. (Aquifer storage programs use surface spreading and infiltration or direct injection through wells to store excess surface water in the aquifer for later recovery through groundwater pumping.) Seepage from irrigation canals is specified either as a recoverable loss fraction or as an individual time series for each simulated diversion, and seepage from bypasses is specified as a recoverable loss fraction for each bypass; these seepage volumes are applied directly to the water table in selected model elements. Aquifer storage programs are simulated as surface water diversions allocated as recharge directly to the water table in specified elements by using a recoverable loss of 95%.

Both recharge and net deep percolation in the Central Valley have increased through time (Figure 72) with significant annual variations. Both the recharge and net deep percolation components rise in wet years (with increased precipitation and surface water availability) and fall in dry years. The average annual volume of water reaching the water table increased from approximately 5 MAF/yr in the 1920s to a maximum of more than 12 MAF/yr in the early 1980s. The net deep percolation volume is greater than recharge from surface water diversions and bypasses (Figure 73). Net deep percolation is greater than recharge in all regions, and significantly greater in all but the Tulare Basin, where there are many aquifer storage programs.

Agricultural land generally has a higher infiltration rate than native vegetation because the soil has been tilled (Scanlon et al., 2005), and also receives more water than native vegetation. Thus the net deep percolation rates of agricultural lands are significantly greater than native vegetation. Historical deep percolation rates increased as the land area devoted to agricultural and urban use expanded (Figure 74). Agricultural net deep percolation rises in wet years and falls in dry years. Urban net deep percolation does not fluctuate as much, and has increased steadily as the urban area increased. Native and riparian net deep percolation varies significantly between wet and dry years.

Figure 72. Simulated Central Valley recharge and deep percolation, 1922-2009.

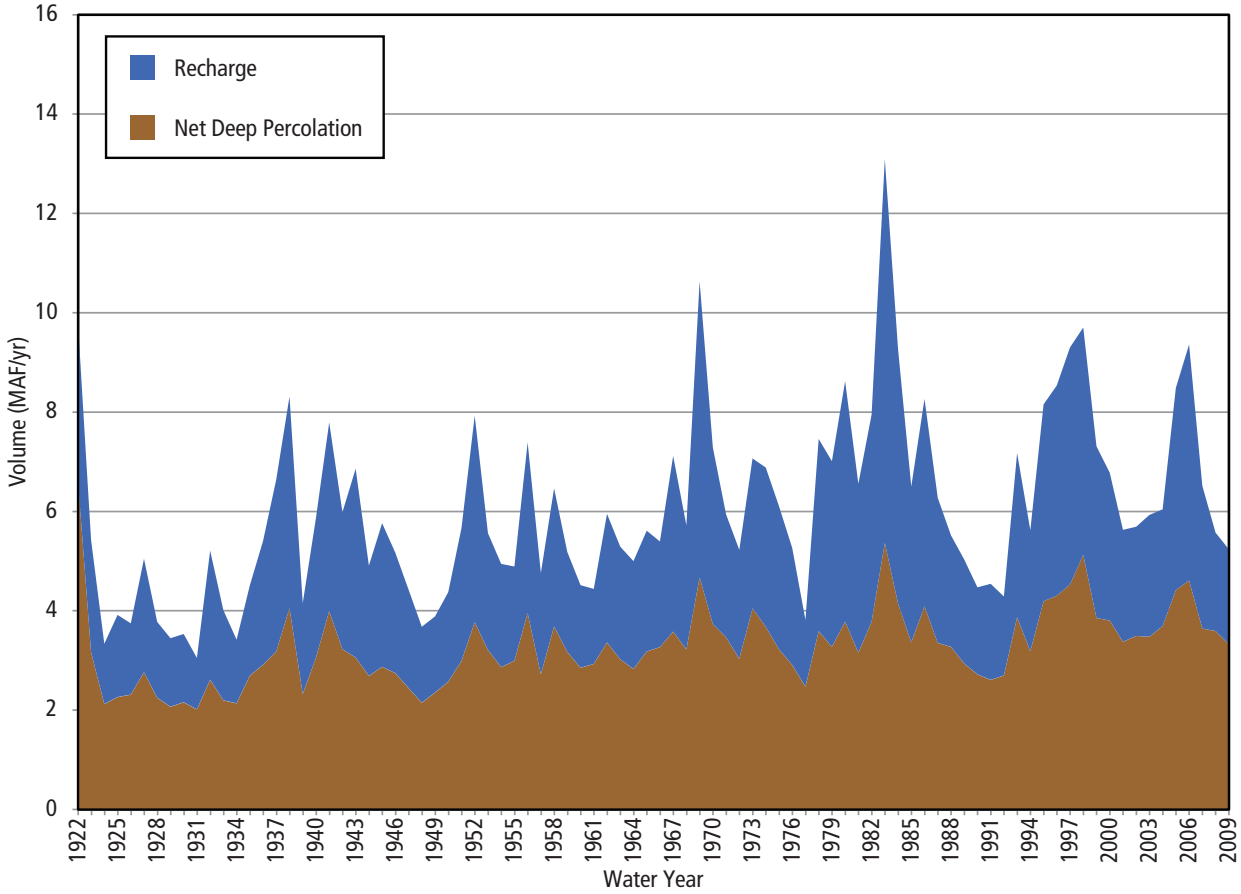


Figure 73. Geographical distribution of recharge and deep percolation, 2000s.

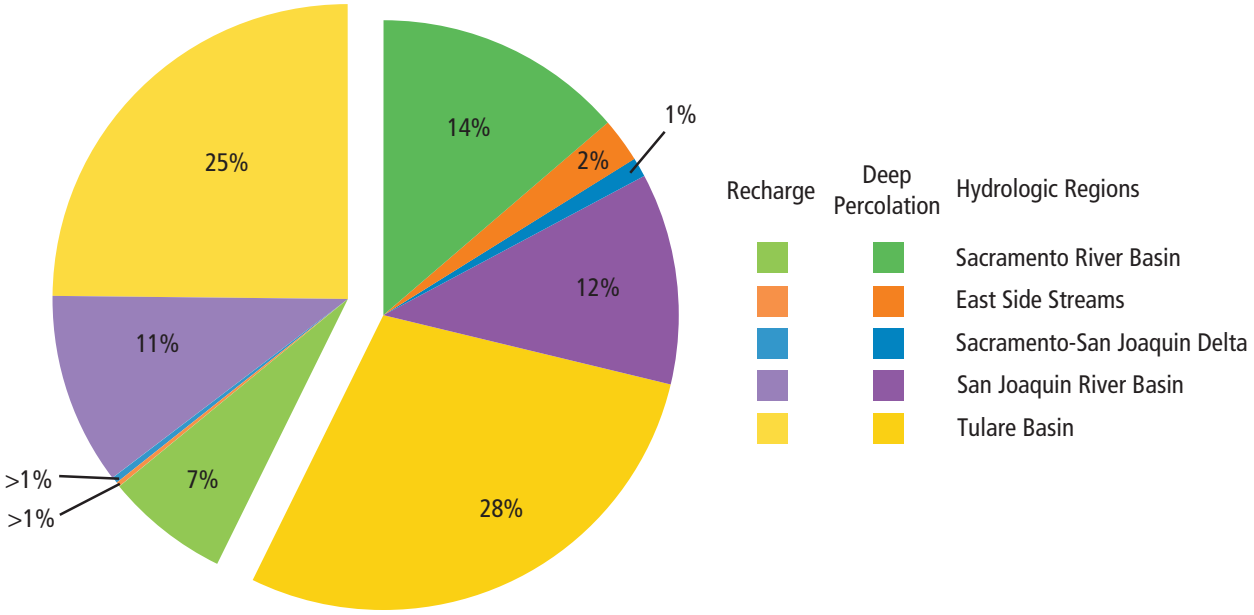
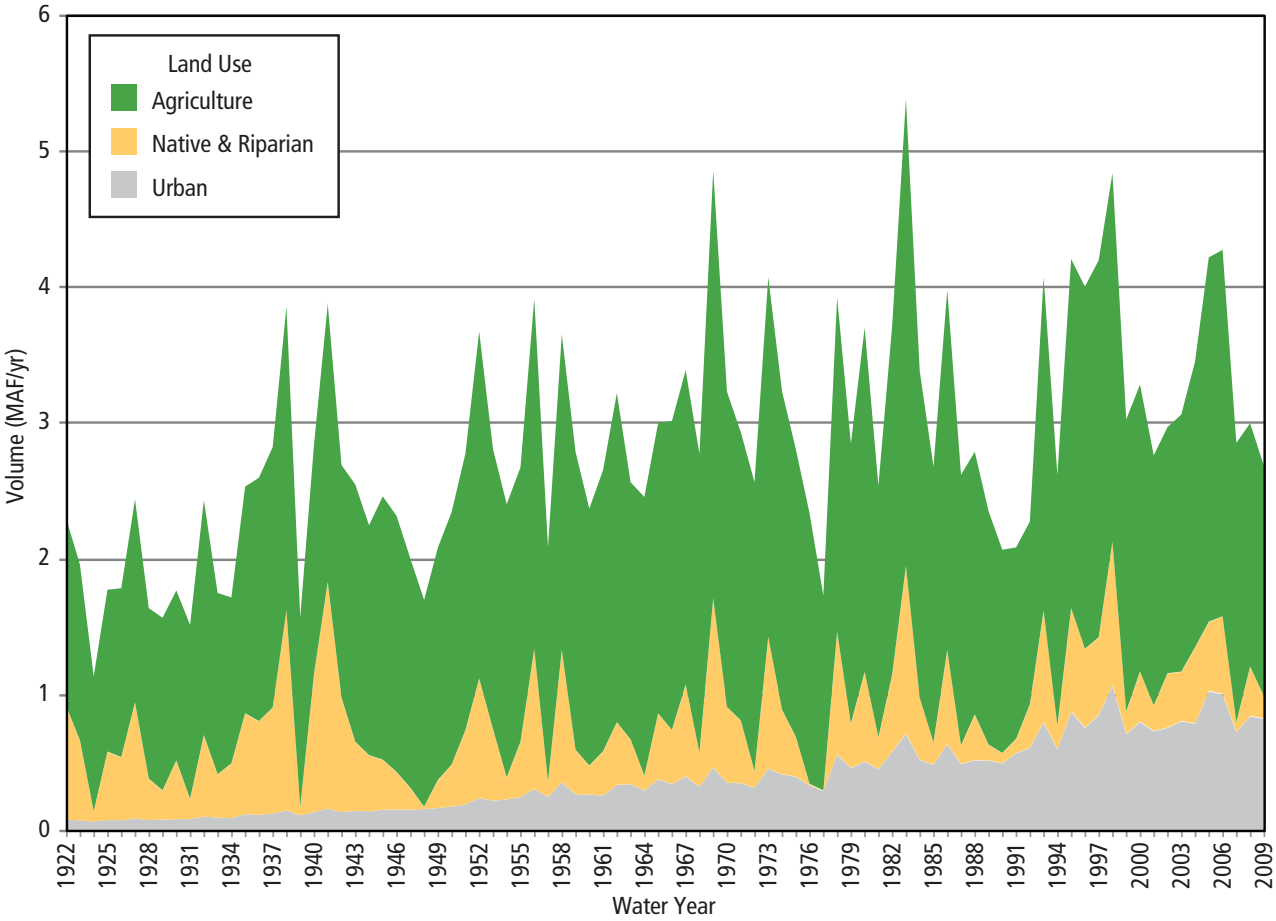


Figure 74. Simulated Central Valley deep percolation for each land use type, 1922-2009.



A comparison of the net deep percolation volumes for the three major hydrologic regions reveals that agricultural sources have dominated net deep percolation in the more arid Tulare and San Joaquin River Basins since the 1920s (Figure 75). Net deep percolation in the Sacramento River Basin was dominated by agriculture in dry years and by native vegetation in wet years through at least the 1940s, but steady land use conversion led to agriculture dominating the net deep percolation after approximately 1960. As the net deep percolation volume increased through time, the proportion of Central Valley deep percolation occurring in the Tulare Basin increased owing to the large proportion of agricultural development in this region (Figure 76).

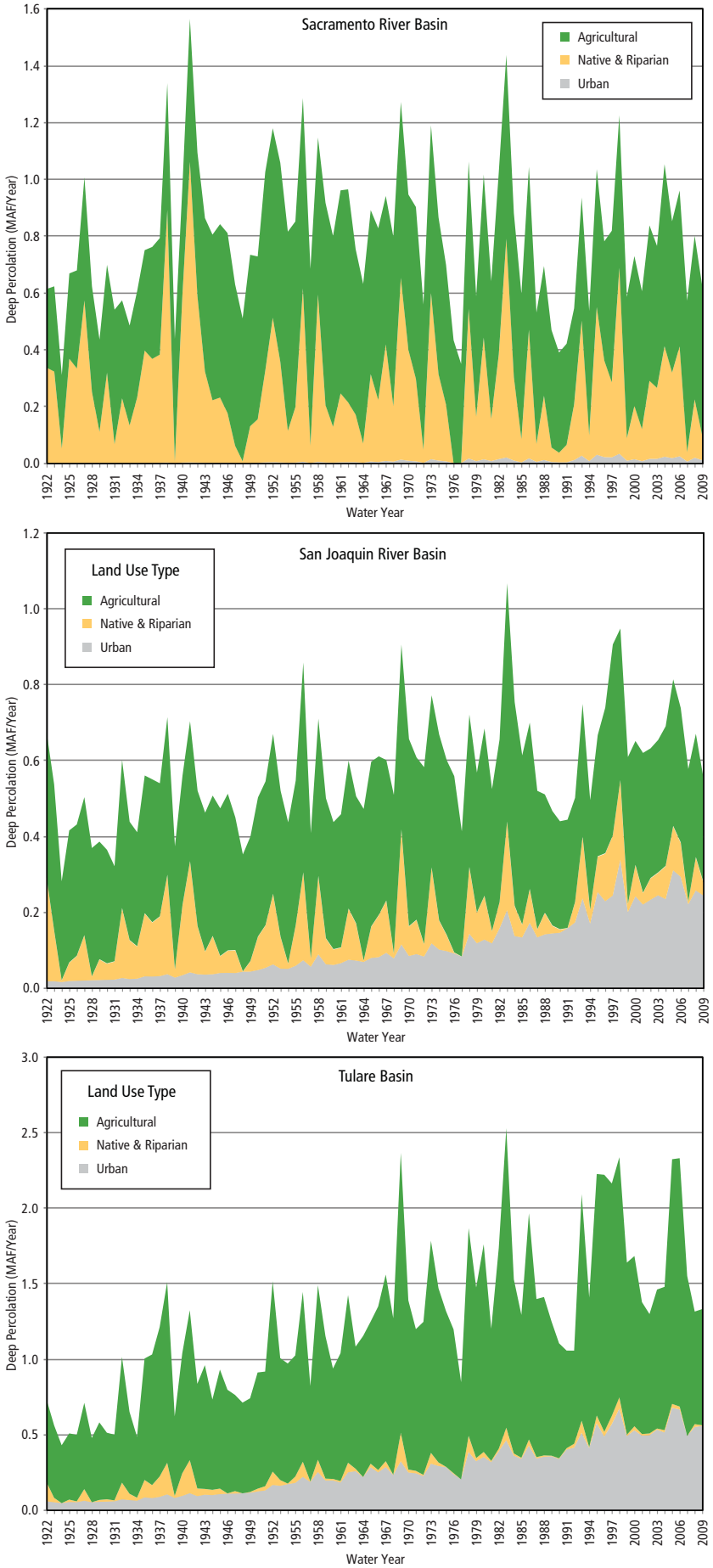


Figure 75. Simulated deep percolation, 1922-2009.

Figure 76. Simulated deep percolation in each hydrologic region.

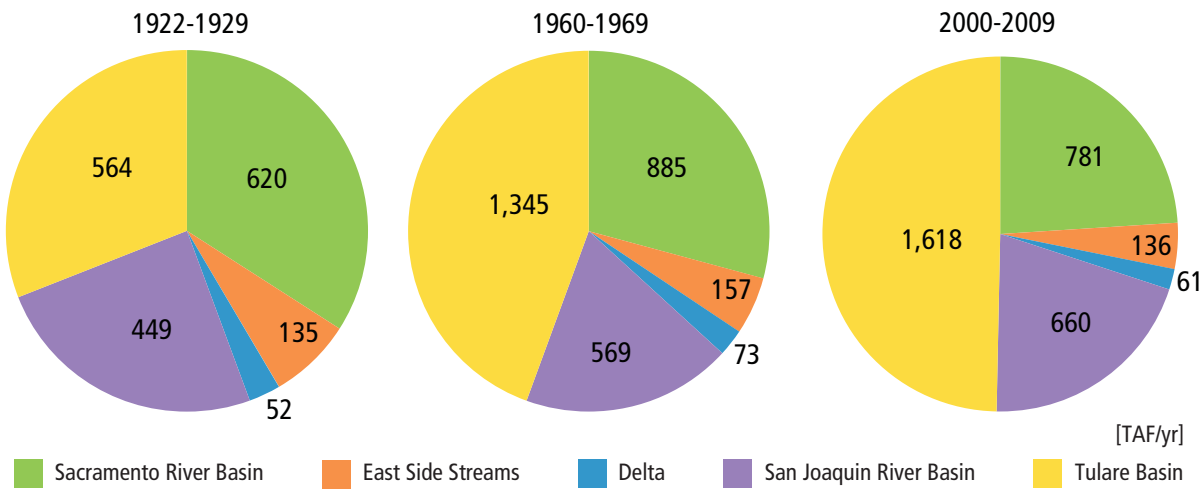
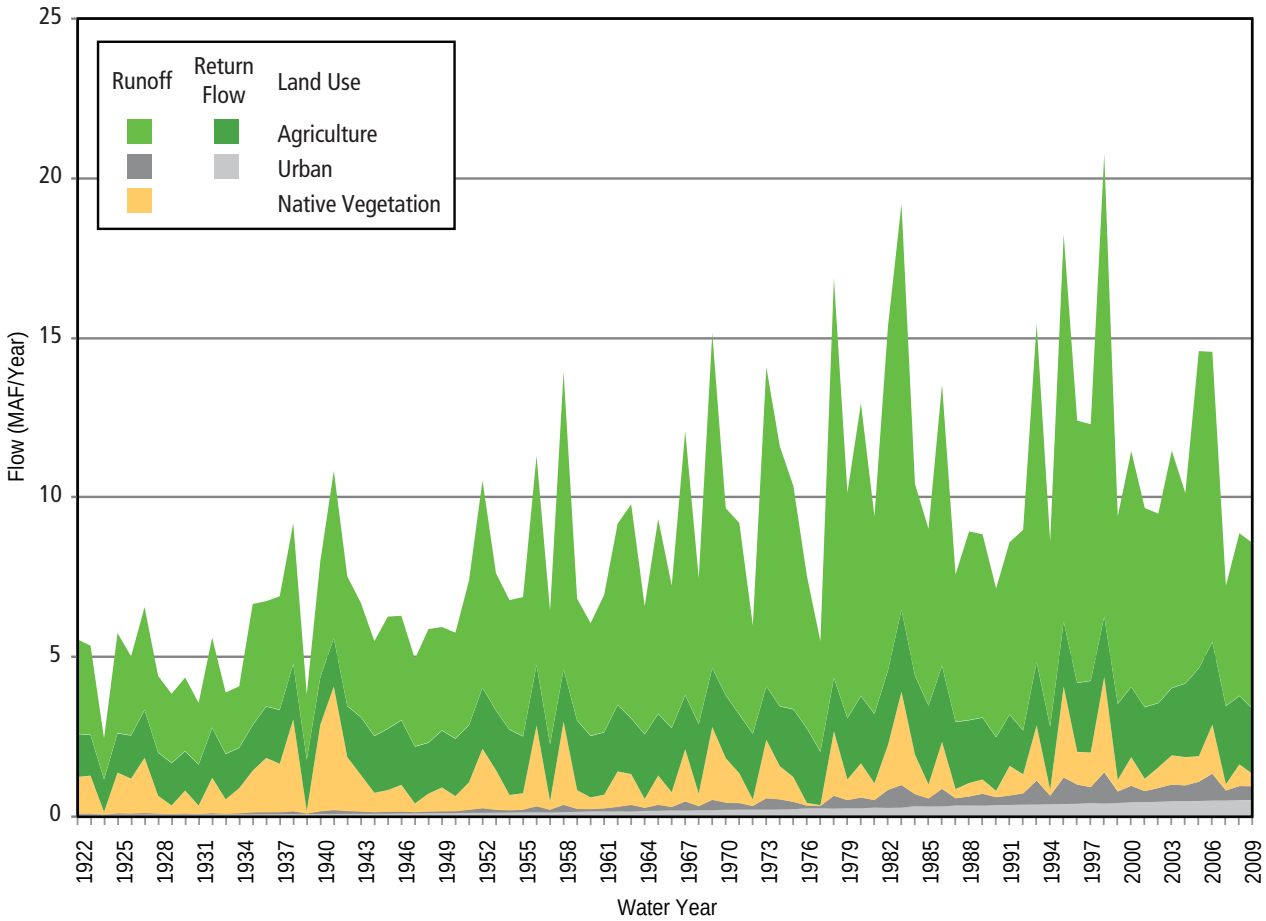


Figure 77. Simulated runoff and return flow for California's Central Valley, 1922-2009.



Runoff and Return Flow

Within the IWFM application, precipitation is partitioned into infiltration and runoff, and irrigation water is partitioned into infiltration and return flow. The volumes of runoff and return flow from agriculture have increased steadily through time (Figure 77). The runoff volume is greater than the return flow volume, and also varies significantly between wet and dry years for both the agricultural and urban land use classes. Runoff and return flows from agricultural lands are greater than those from native vegetation and urban land uses, although the urban runoff and return flows have also increased steadily through time.

The Sacramento River Basin has historically contributed around 40% of the total runoff and return flow volume, even though the Tulare Basin is much larger (Figure 78). The runoff volumes from subregions north of the Sacramento-San Joaquin Delta are significantly greater than those from subregions south of the delta (Figure 79), owing to their higher precipitation volumes. The largest simulated return flow volumes occur in subregions 3 and 5 in the central part of the Sacramento River Basin, and the smallest in subregions 18, 19 and 21 in the Tulare Basin (Figure 80).

Figure 78. Regional distribution of simulated runoff and return flow.

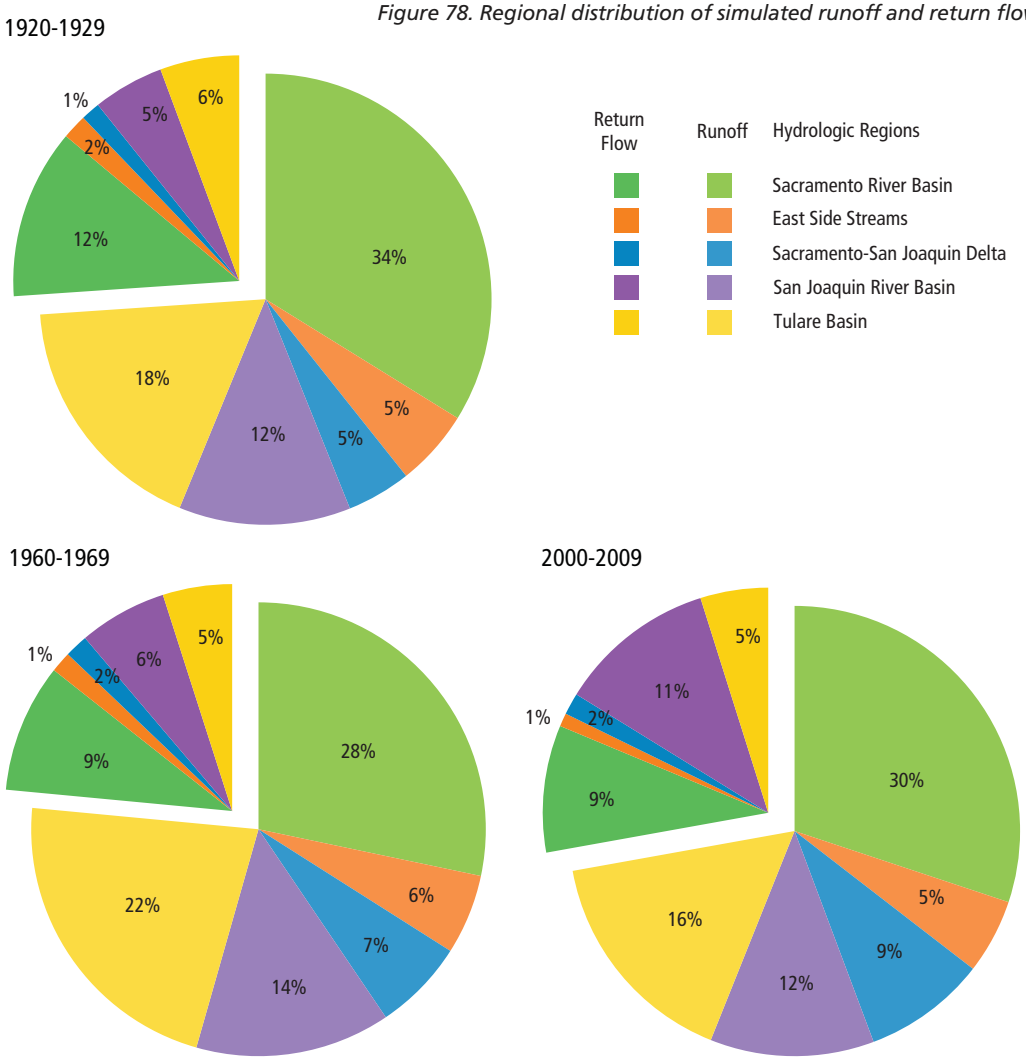


Figure 79. Simulated average annual runoff volume, 2000-2009.

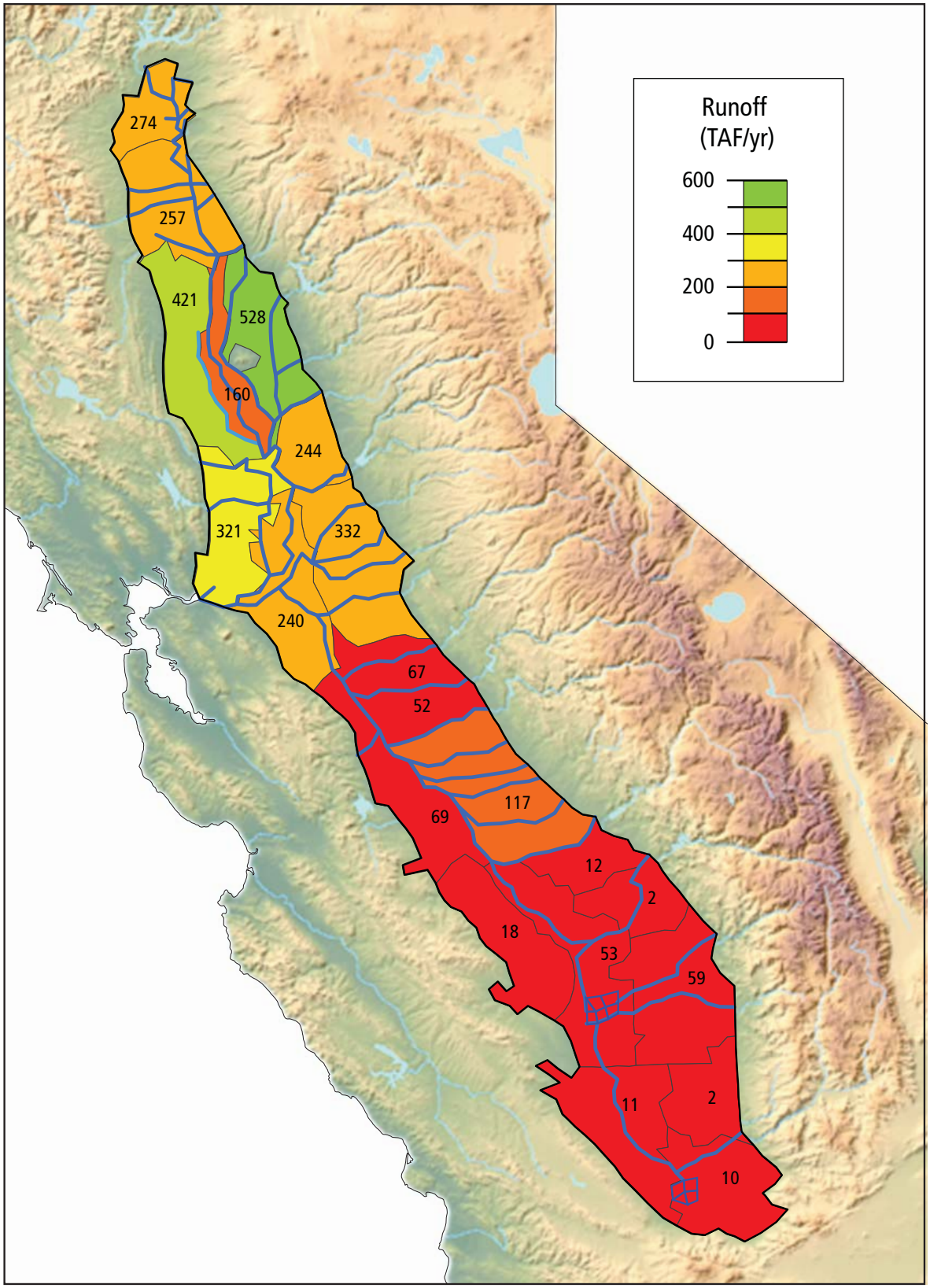
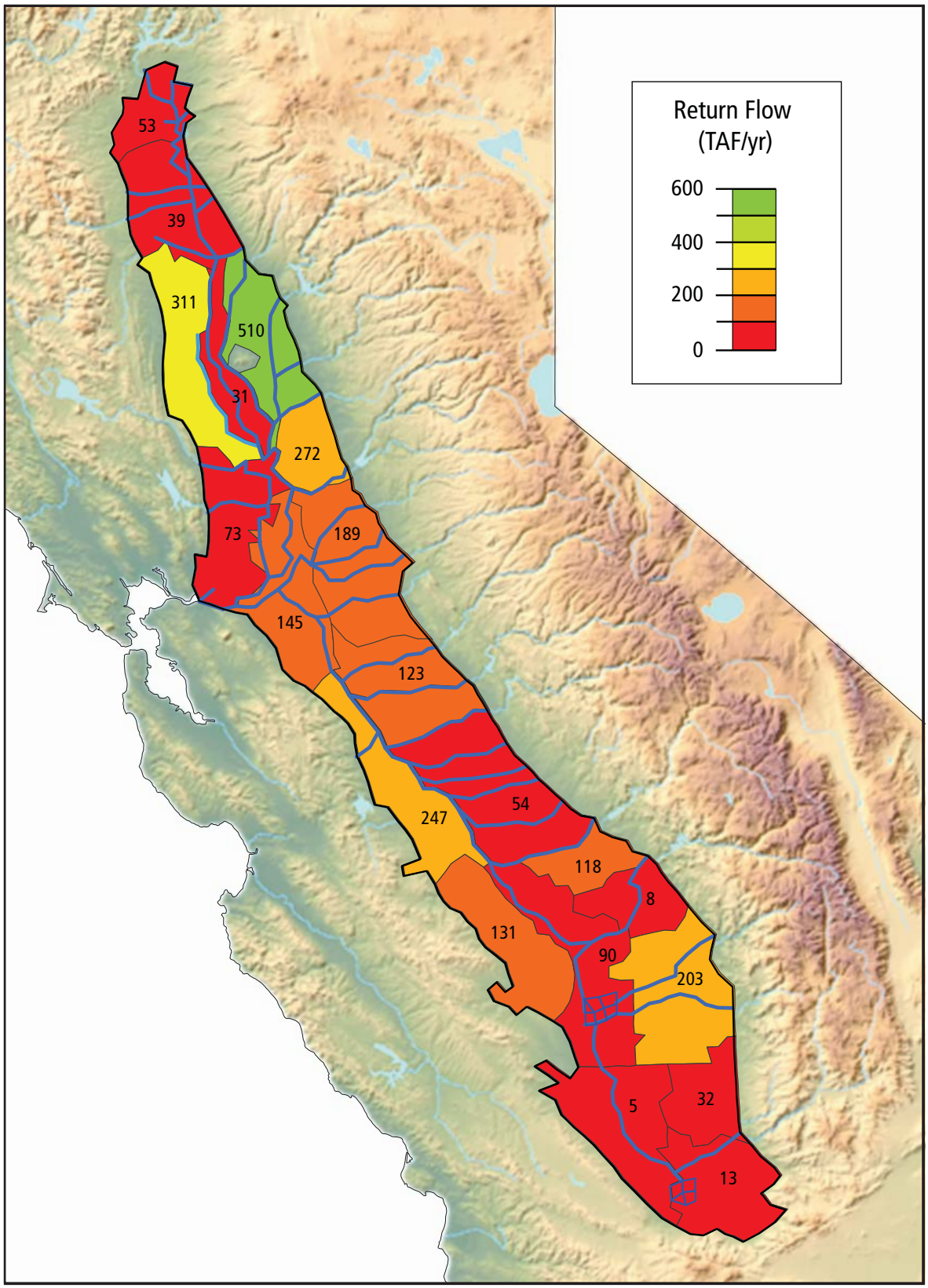


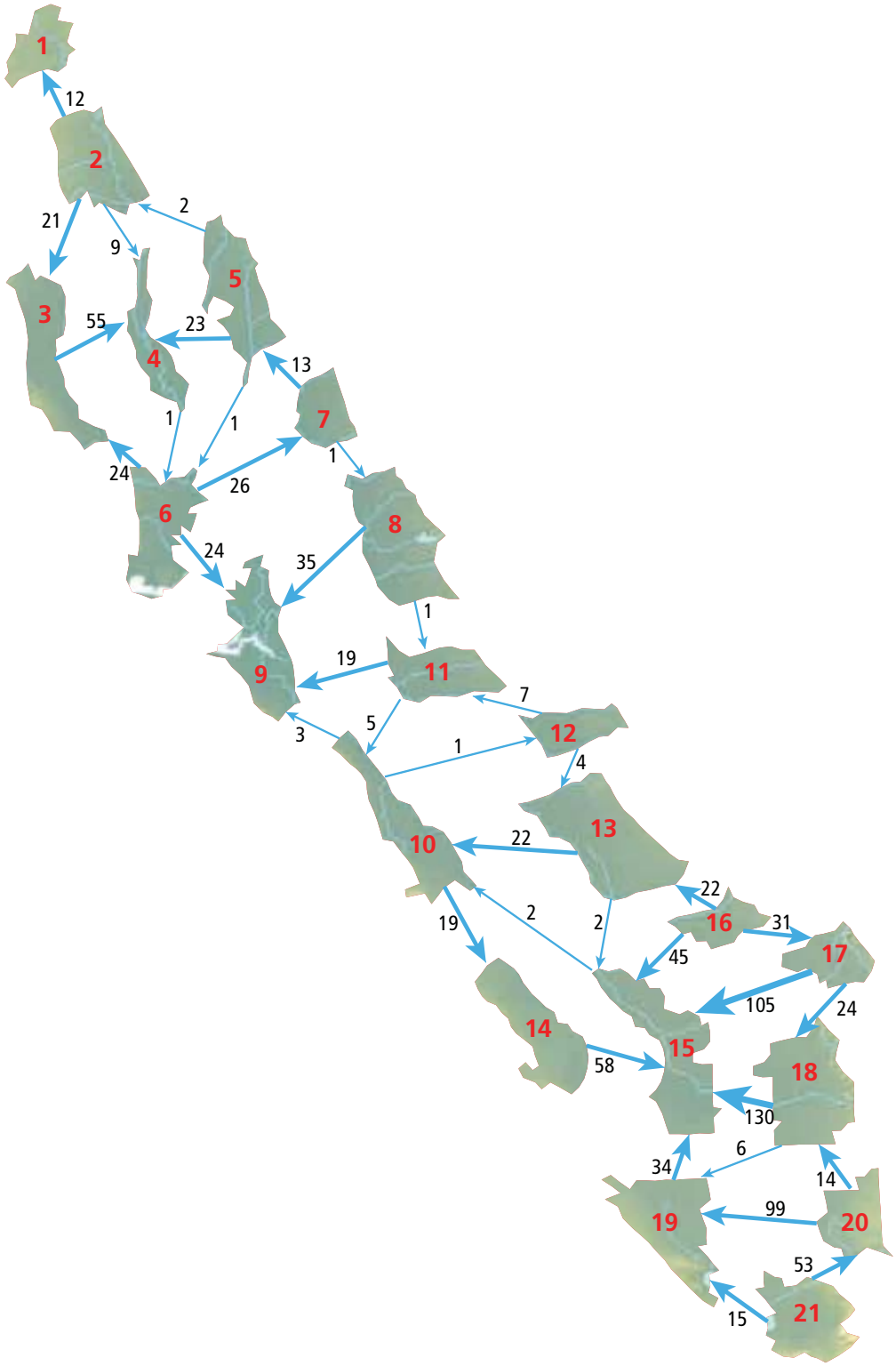
Figure 80. Simulated average annual return flow volume, 2000-2009.



Boundary Flows

Historical changes in groundwater flow patterns are reflected in the lateral groundwater flows between model subregions (Figure 81). In the 1920s, the groundwater flow system was generally dominated by deep percolation and stream-aquifer inflows, with discharges to rivers and in some areas to groundwater pumping. This is reflected in the groundwater flows between model subregions. As groundwater pumping rates increased throughout the valley, groundwater flow directions changed in some areas as water flowed towards areas of higher groundwater pumping. The volume of groundwater flowing between subregions is much smaller than the volume of surface water flowing between subregions.

Figure 81A. Simulated average annual subsurface flows between subregions, 1922-1929.



[Thousand acre-feet per year]

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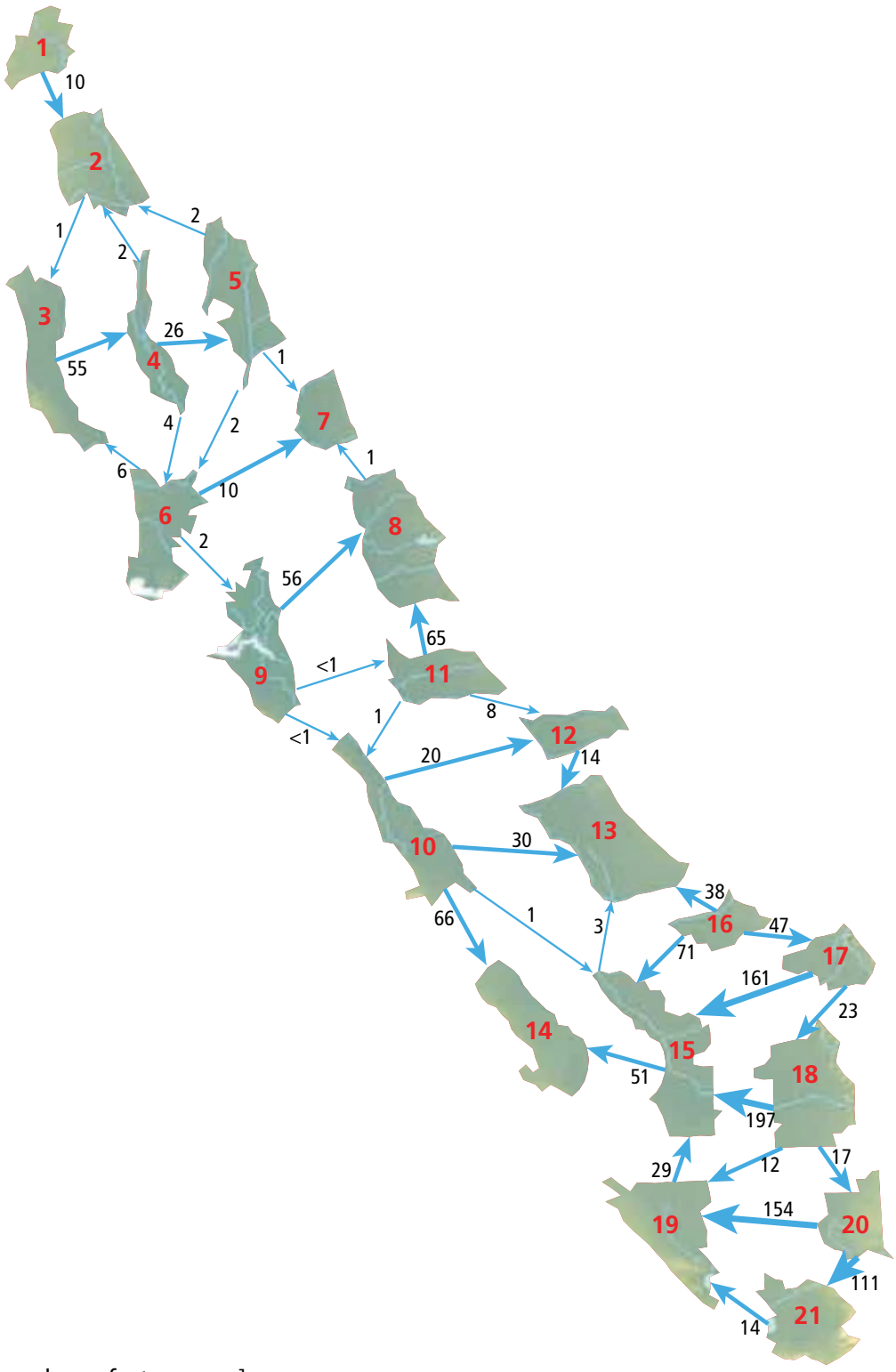
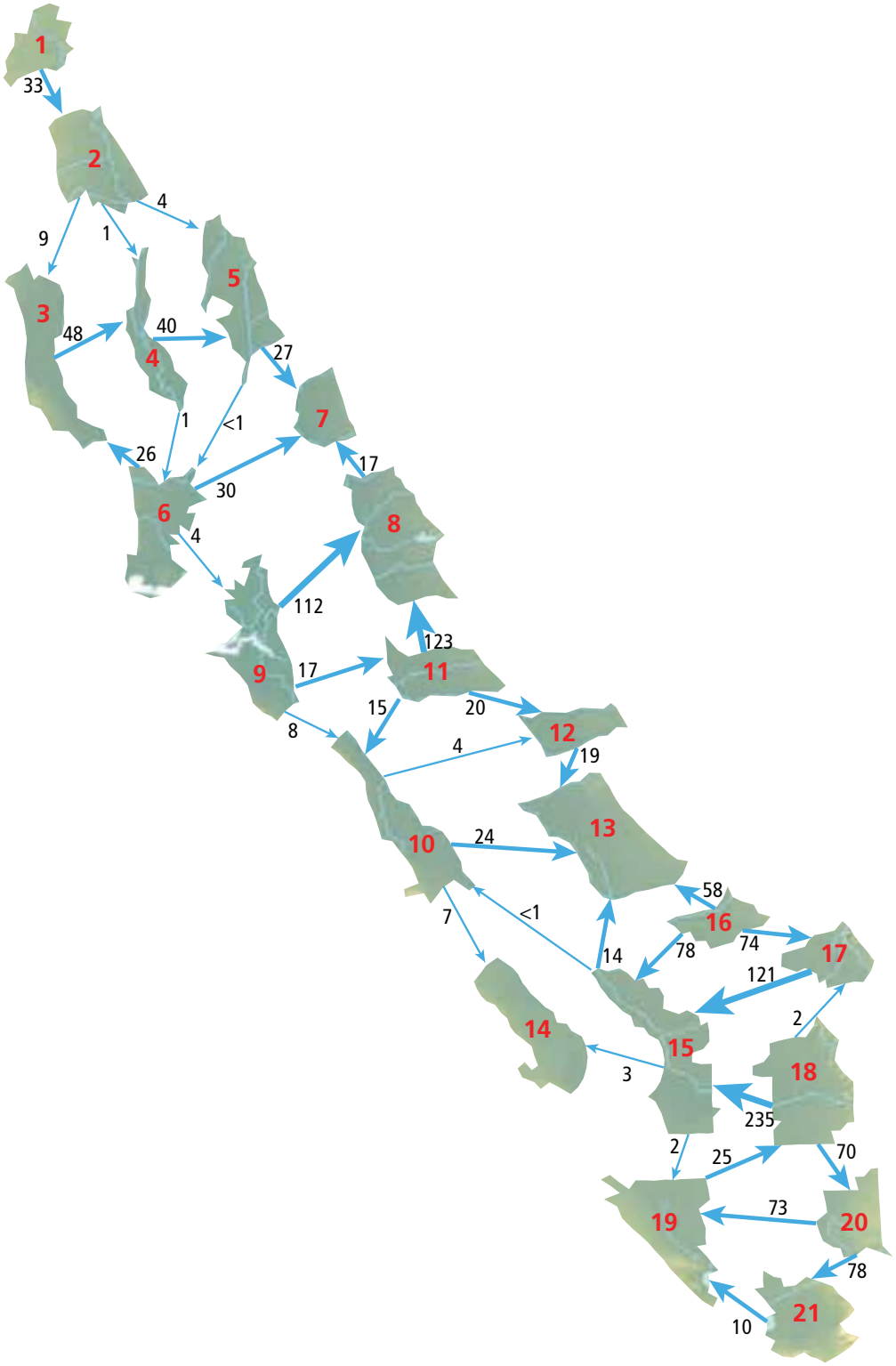
Figure 81B. Simulated average annual subsurface flows between subregions, 1960-1969.



[Thousand acre-feet per year]

Figure 81C. Simulated average annual subsurface flows between subregions, 2000-2009.

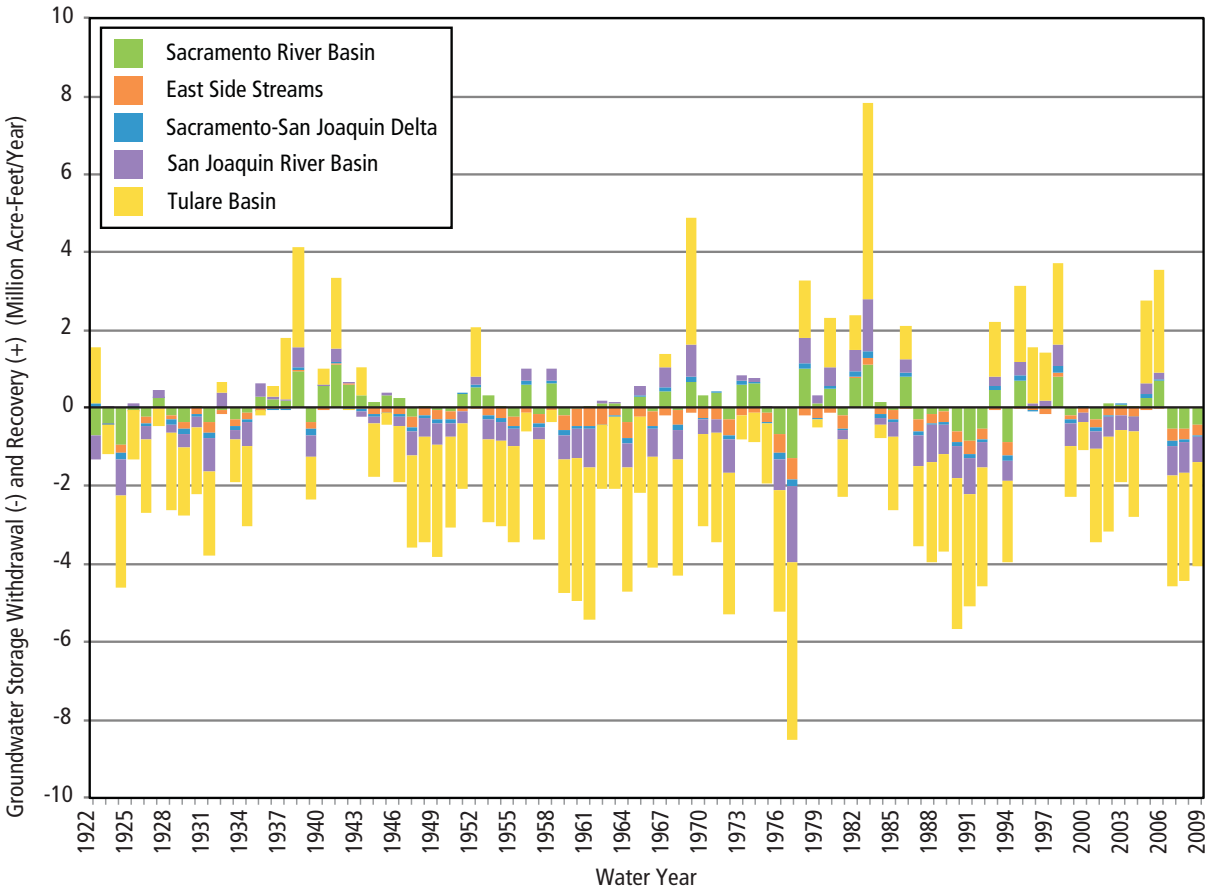


[Thousand acre-feet per year]

Change in Storage

The Central Valley groundwater system is a large water storage reservoir that is distributed throughout the valley. Some agricultural and urban users rely exclusively on groundwater, and others use it to supplement surface water supplies. In dry years, groundwater pumping in excess of replenishment reduces the amount of water stored in the aquifer. In wet years, groundwater pumping is reduced and the amount of water stored in the aquifer increases. The amount of water flowing into and out of storage has fluctuated significantly between regiona and from year to year (Figure 82) with large reductions in dry years and large recoveries in wet years. Significant effects, such as land surface subsidence and the groundwater heads falling below well screens, are more common after several consecutive years of net groundwater withdrawals. One such period occurred from 1944 to 1977, a 34-year period with only four years of net groundwater storage recovery. Significant land-surface subsidence was documented throughout the Central Valley during this period (Lofgren and Ireland, 1973; Poland et al., 1975; Ireland, 1986).

Figure 82. Simulated annual change in Central Valley groundwater storage, 1922-2009.



The total volume of water stored in the Central Valley aquifer declined by nearly 130 MAF between 1922 and 2009 (Figure 83). During this period, there was an increase in water storage in the Sacramento River Basin, and net declines in the other regions. The regional declines mirror the precipitation distribution and the availability of surface water supplies, with greater declines occurring in the arid areas with limited access to surface water supplies, and thus less recharge and more groundwater pumping. Most of this decline occurred in the Tulare Basin, where water demands have consistently been greater than the available surface water supply.

A comparison between the annual withdrawal and recovery rates and the cumulative change in groundwater storage for the five hydrologic regions shows that groundwater levels have generally risen in the Sacramento River Basin and fallen in the other four regions (Figure 84). The rise in the Sacramento River Basin is most likely due to a combination of factors including higher rates of deep percolation, more abundant surface water supplies, and lower rates of groundwater pumping (Figure 85). The Sacramento River Basin, Sacramento-San Joaquin Delta and San

Figure 83. Simulated cumulative change in Central Valley groundwater storage, 1922-2009.

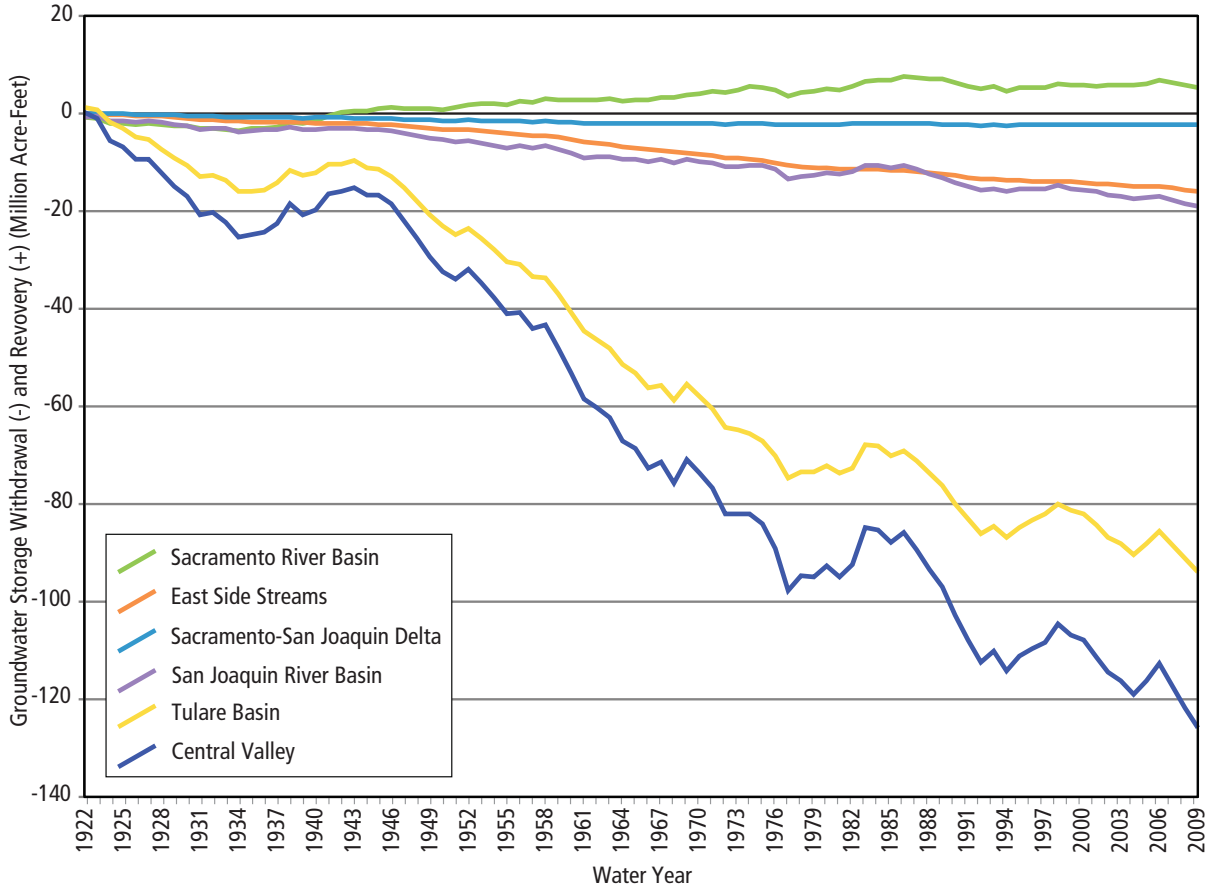


Figure 84. Simulated regional change in groundwater storage in California's Central Valley, 1922-2009.

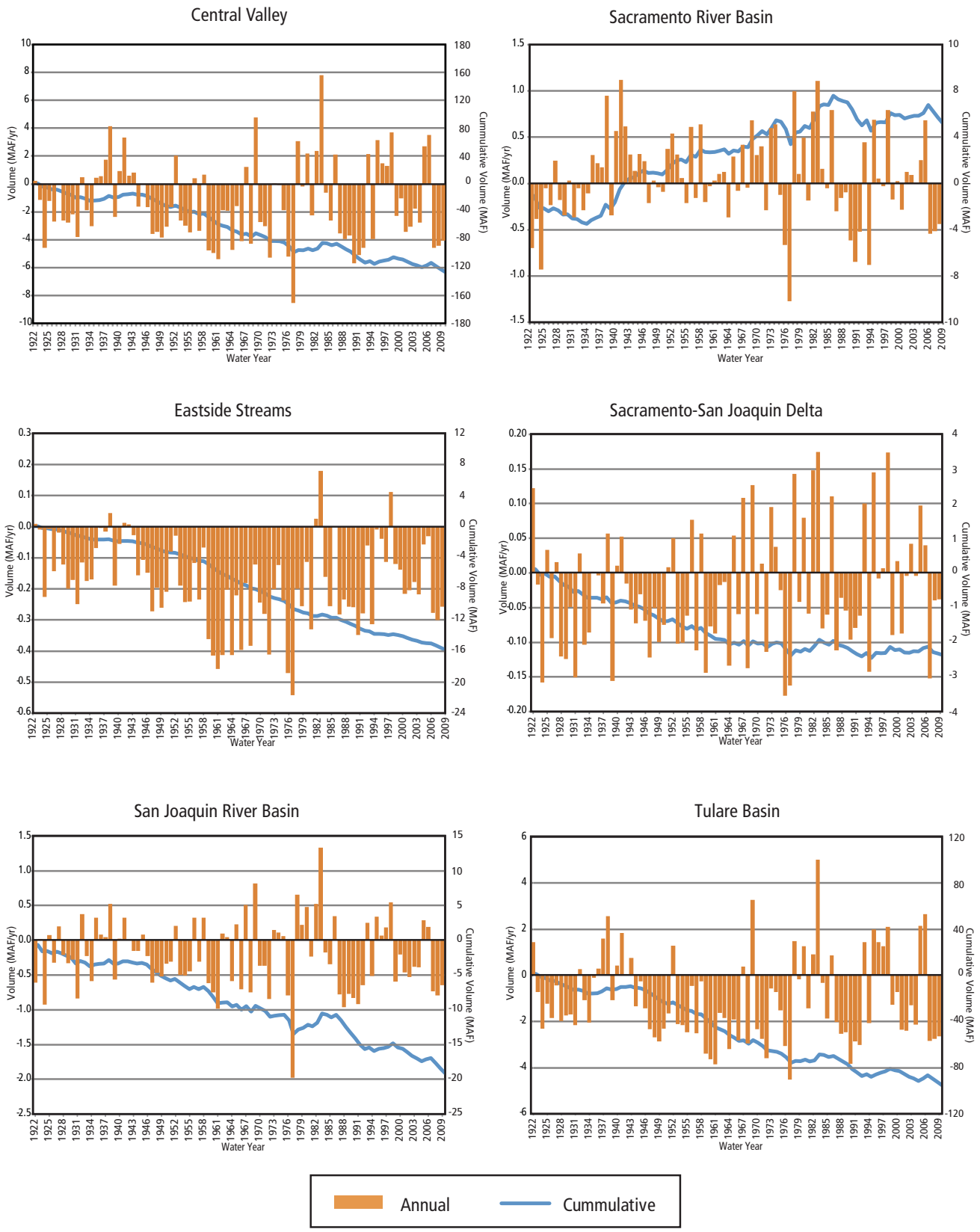
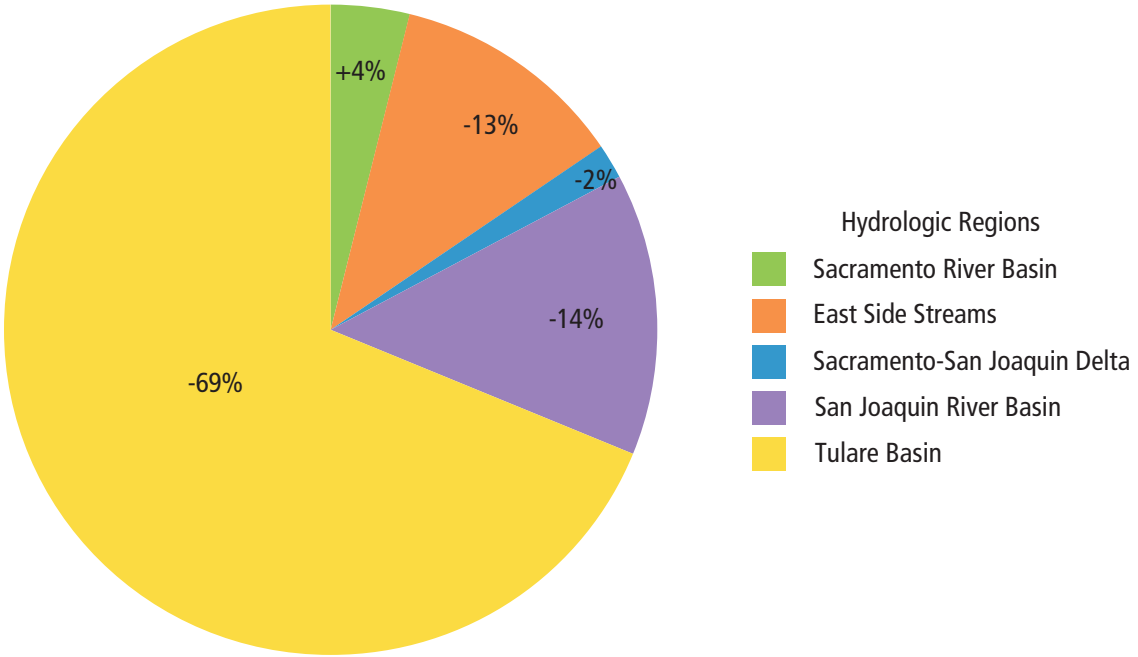


Figure 85. Simulated regional distribution of the change in groundwater storage, 1922-2009.2009.



Joaquin River Basin regions show a regular pattern of moderate withdrawals and recoveries. Two regions, the Eastside Streams and Tulare Basin, show long periods dominated by withdrawals. Between 2000 and 2009, nearly 70% of the total decline in Central Valley groundwater storage occurred in the Tulare Basin hydrologic region (Figure 86).

These model results suggest that there are areas of persistent groundwater overdraft in the Tulare Basin. Groundwater overdraft is the condition in which the amount of water withdrawn by pumping during the long term exceeds the amount of water that recharges the groundwater basin. Overdraft is characterized by groundwater levels that decline during a period of years and never fully recover, even in wet years. Overdraft can lead to increased extraction costs, land subsidence, water quality degradation, and environmental effects. Small water systems and private well owners often rely on shallow wells, and can experience water shortages when groundwater levels decline below the depths of their wells.

Maps of net change in groundwater storage for three representative decades (Figure 87) suggest that groundwater overdraft has been persistent in several Tulare Basin subregions since the 1920s. The greatest net withdrawals occurred in the 1960s. The importation of surface water through the California Aqueduct and the widespread implementation of conjunctive use practices after the 1960s reduced regional reliance on groundwater to some extent. The C2VSim subregions with the greatest groundwater withdrawals over the simulation period are concentrated on the western side of the Tulare Basin (Figure 88).

Figure 86. Simulated regional distribution of the change in groundwater storage, 2000-2009.

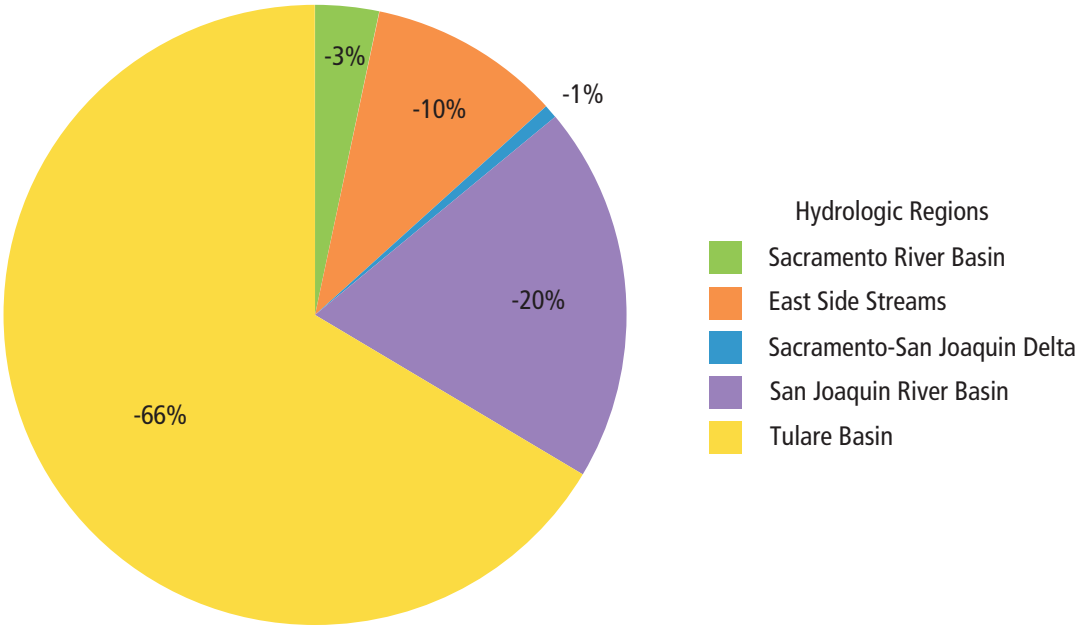


Figure 87A. Simulated average annual change in groundwater storage, 1922-1929.

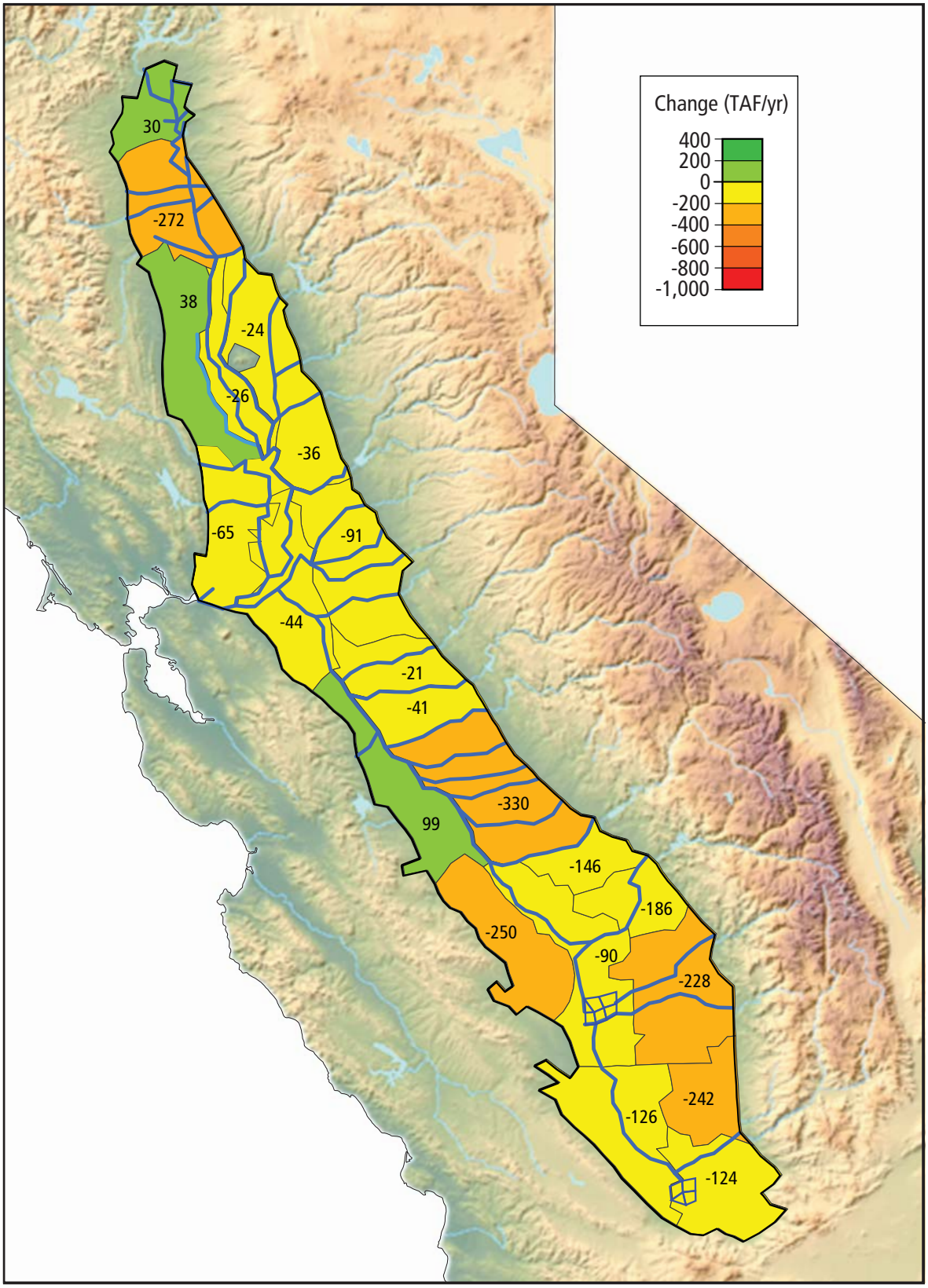


Figure 87B. Simulated average annual change in groundwater storage, 1960-1969.

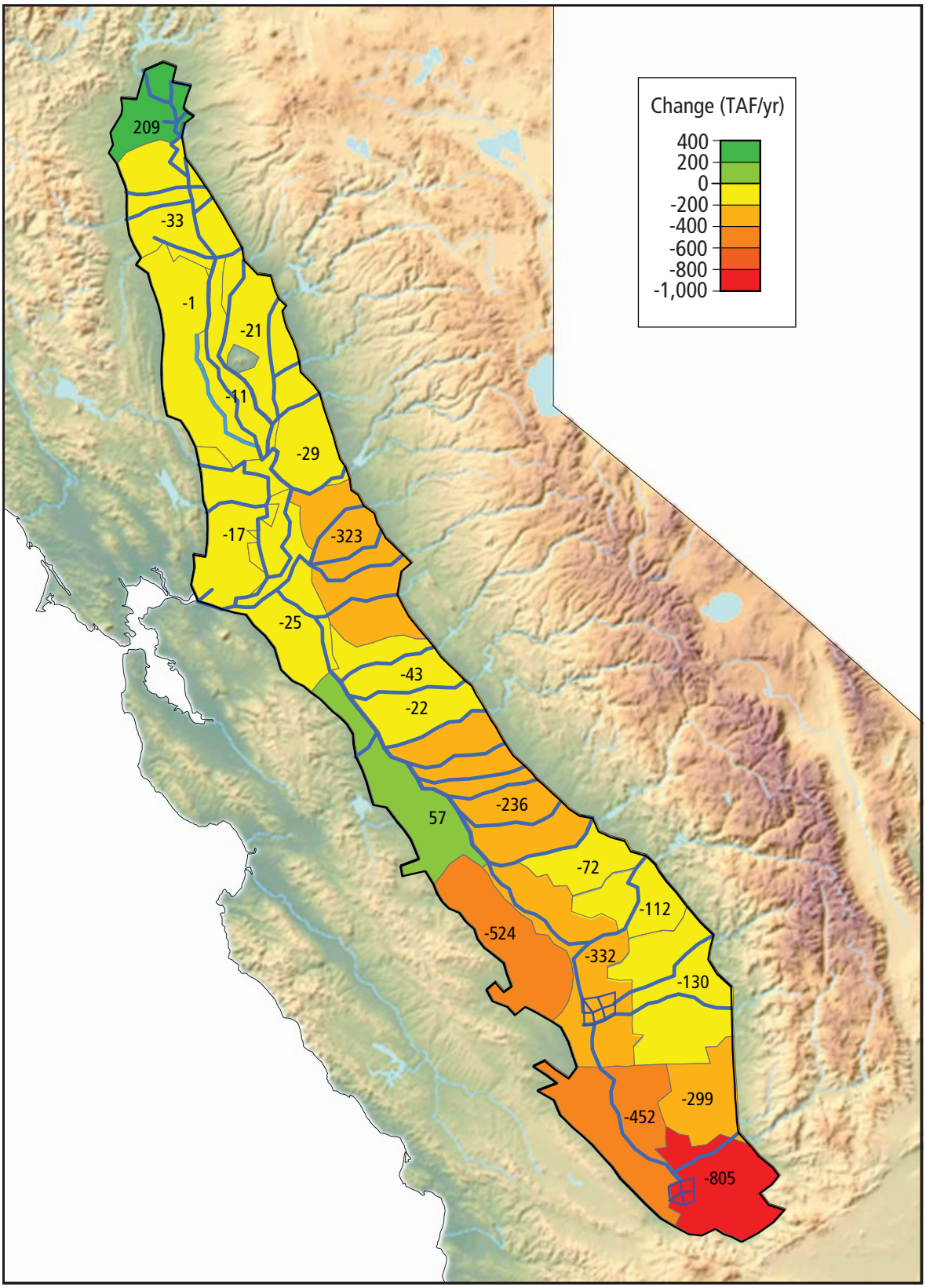


Figure 87C. Simulated average annual change in groundwater storage, 2000-2009.

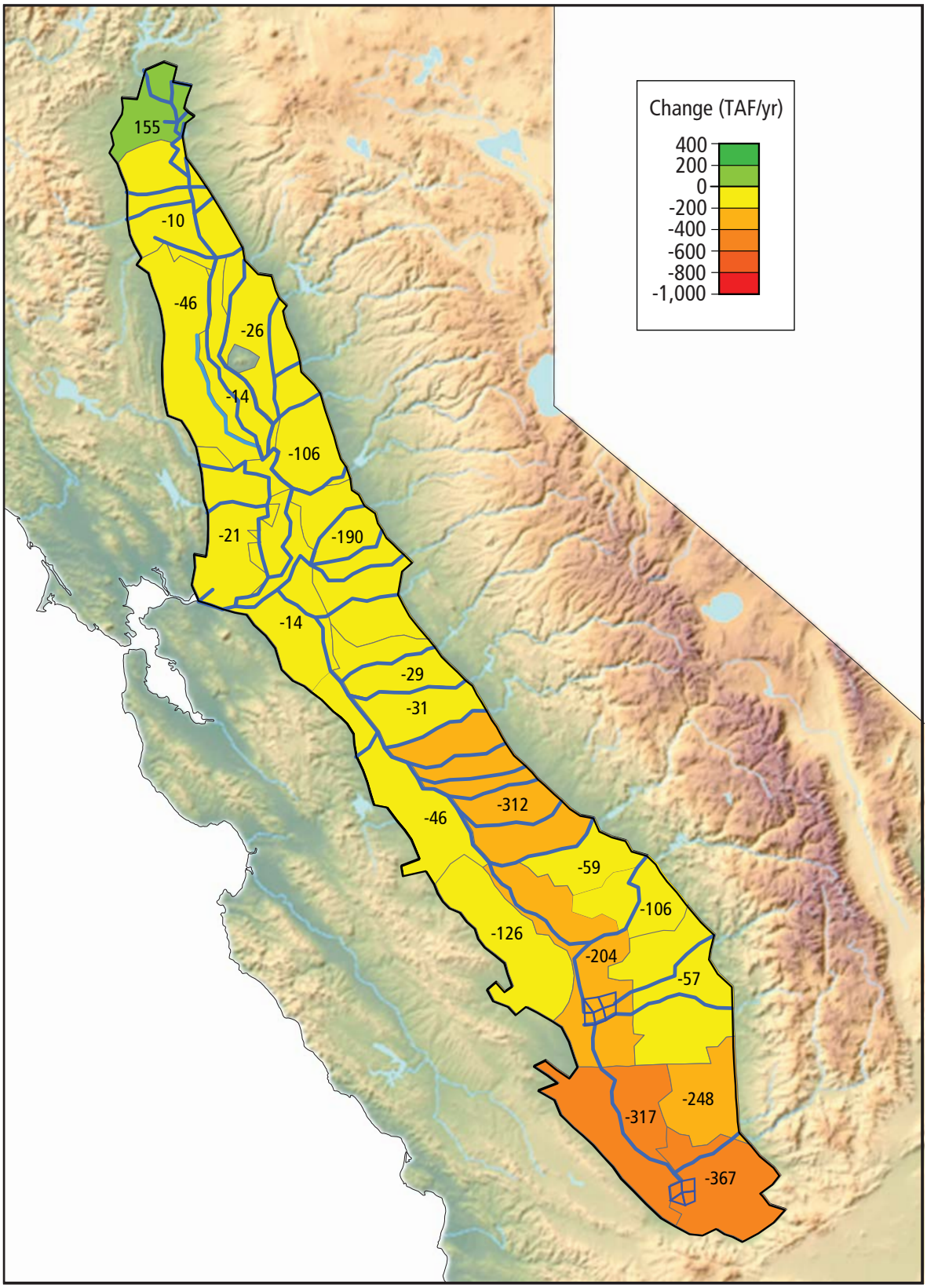
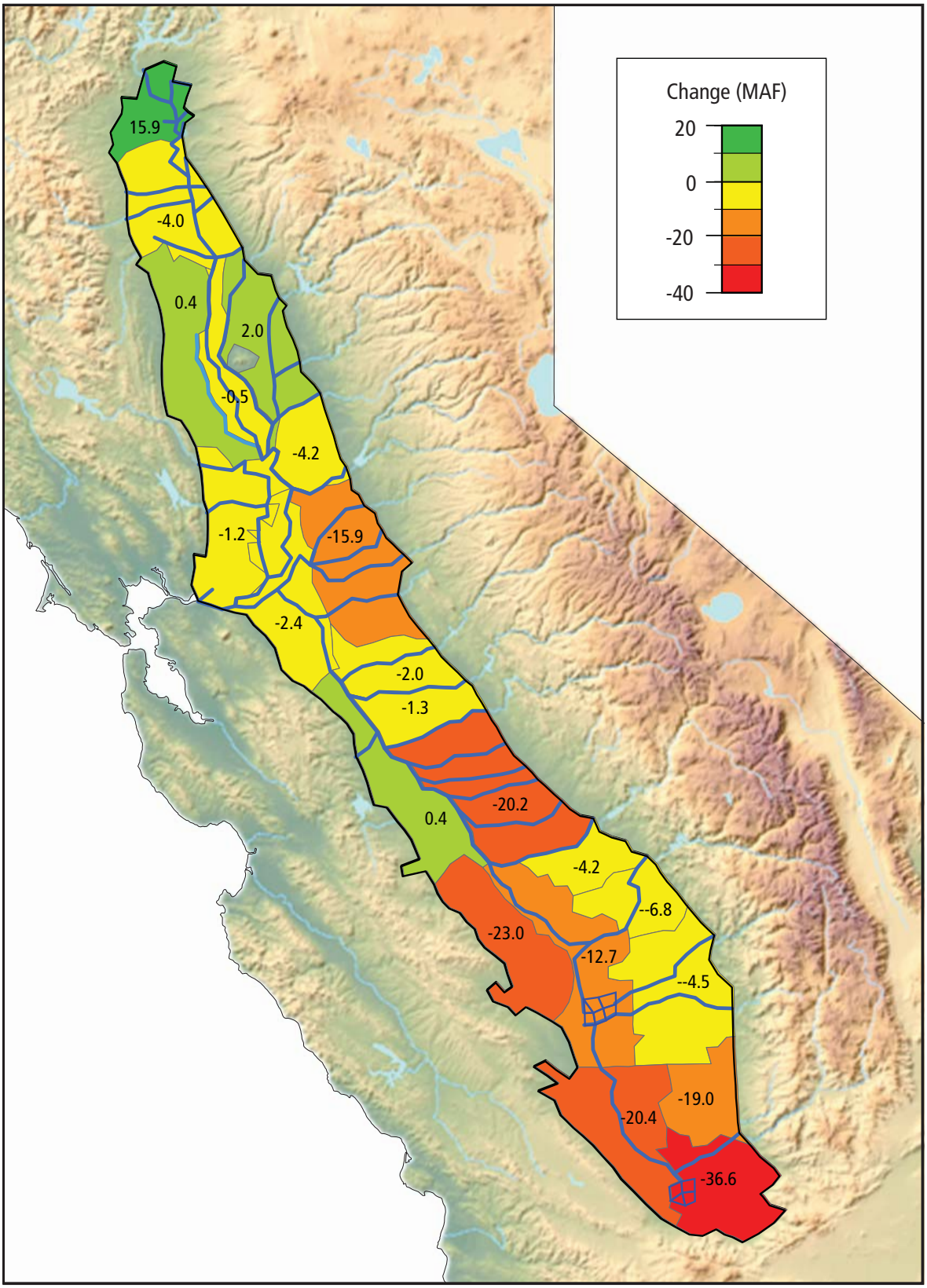


Figure 88. Simulated cumulative change in groundwater storage, 1922-2009.



Land-Surface Subsidence

Groundwater extraction in excess of replenishment rates can have a dramatic impact on the land surface. When the groundwater heads drop significantly, some of the weight of the overlying sediments shifts to the aquifer sediments, which compress slightly, lowering the altitude of the land surface. In most aquifer sediments, this weight will be supported by the water when the groundwater head returns to previous levels, and the land surface altitude will rebound; this is called elastic subsidence, and occurs seasonally in many regions. However, permanent land surface subsidence can occur where a portion of the aquifer is composed of fine-grained sediments and the groundwater heads drop to levels that have never previously been experienced by these sediments. In these areas, the aquifer sediments undergo permanent deformation, called inelastic subsidence, when they are subjected to the lower groundwater heads. Significant permanent land surface subsidence due to groundwater extraction has been observed in several areas in the Central Valley (Ireland, 1986).

The USGS conducted extensive monitoring of land surface subsidence in the Central Valley between approximately 1960 and 1980, but little data exists regarding the extent of land surface subsidence outside this period. The C2VSim model can be used to estimate the locations and extent of pumping-induced land-surface subsidence that occurred prior to subsidence monitoring, and after subsidence monitoring ceased. Model results suggest that most land surface subsidence due to groundwater withdrawals has been confined to the Tulare Basin (Figure 89). Subsidence also appears to occur in episodes lasting from several to many years, which correspond to extensive periods of net groundwater withdrawals (Figure 90). In the 1980s, water management practices were changed throughout the areas subject to land surface subsidence to increase the amount of surface water deliveries and reduce groundwater pumping.

A graph of simulated cumulative subsidence for water years 1922 to 2009 (Figure 91) shows the greatest rates occurred between the late 1940s and late 1970s. Model results indicate approximately 24 MAF of groundwater storage was lost during this period, a rate of approximately 800,000 AF per year. Although subsidence rates were generally lower after 1980, significant periods of land-surface subsidence occurred between 1987 and 1994 and between 2000 and 2009. Model results indicate approximately 8 MAF of storage was lost to subsidence between 1980 and 2009, a rate of 267,000 AF per year. These results suggest that land surface subsidence due to groundwater overdraft is still a significant problem in the Tulare and San Joaquin River basins.

Figure 89. Simulated cumulative subsidence volume, 1922-2009.

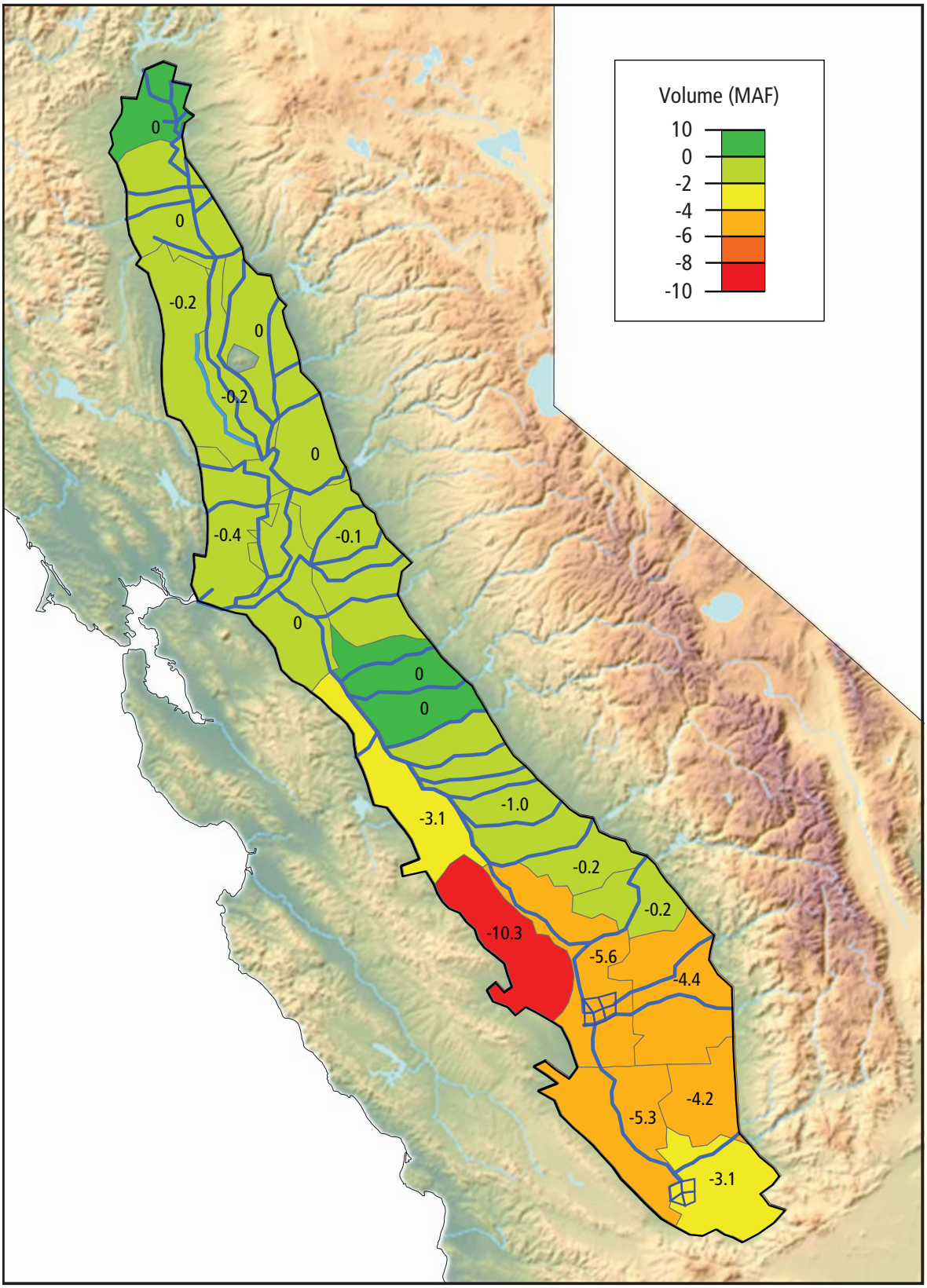


Figure 90. Simulated subsidence from groundwater withdrawals, 1922-2009.

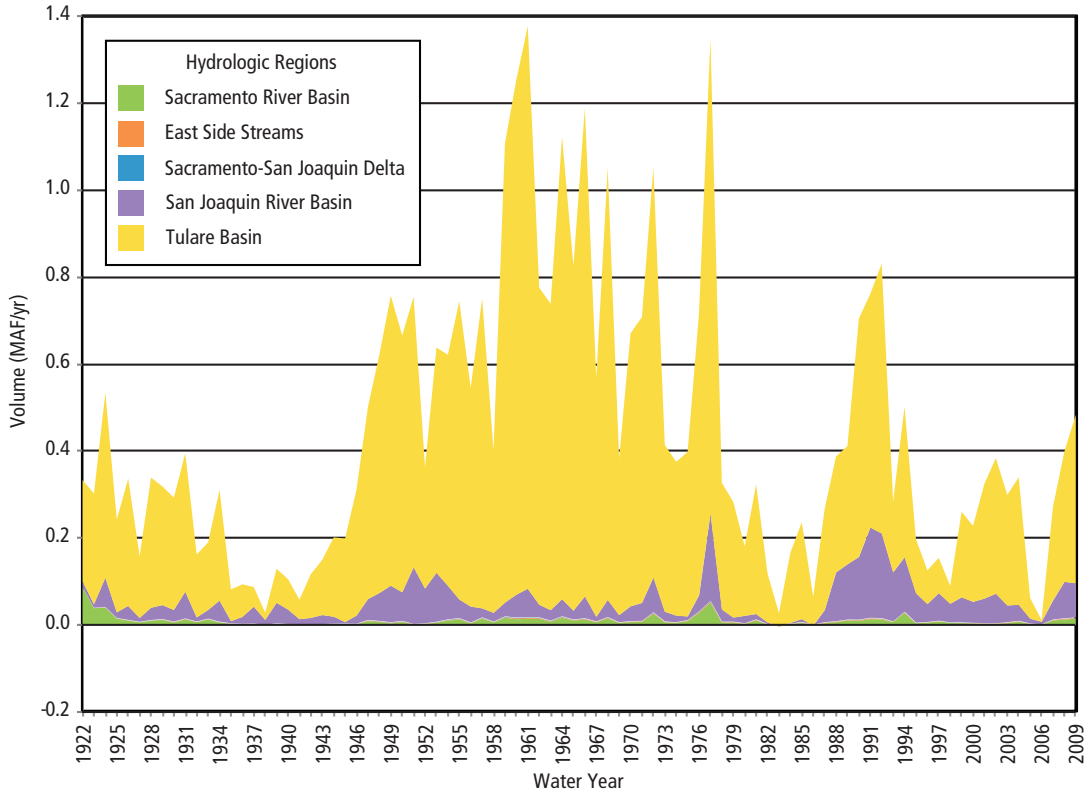
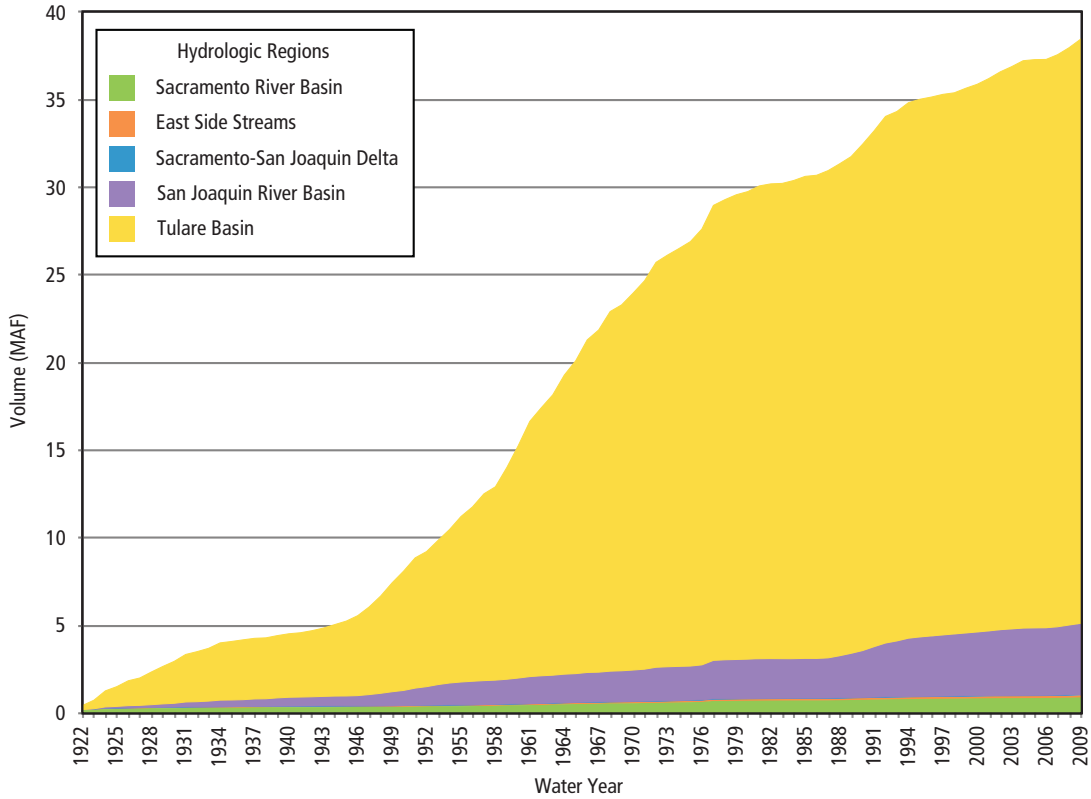


Figure 91. Simulated cumulative subsidence from groundwater withdrawals, 1922-2009.



River-Groundwater Exchanges

The changes to the Central Valley's hydrologic system that occurred between 1922 and 2009 have significantly altered the flow of water between Central Valley rivers and the groundwater aquifer. The gradients governing flows between rivers and adjacent aquifers have been altered by increased depths to the water table and by reduced winter flows and increased summer flows in rivers as inflow patterns changed (Figure 47) and surface water diversions increased. Under pre-development conditions, significant volumes of water seeped into the aquifer from river channels near the valley margins, and significant volumes discharged from groundwater to rivers near the valley trough. During the summer months when rim inflows were low, groundwater discharges near the valley trough provided steady in-stream flows and moderated water temperatures.

The net volume of water discharging from aquifers to rivers in the Central Valley has declined steadily from the 1920s to the present (Figure 92), with net flow into aquifers in most years after 1990. Although the net discharge volume fluctuates from year to year, the average rate has declined from a discharge of approximately 2-3 MAF per year in the 1920s (ignoring the first few years of the simulation period) to flows of up to 1.5 MAF per year into aquifers in the 2000s. The seasonal patterns of river flows to and from groundwater also changed between the 1920s and 2000s (Figure 93). The large summer groundwater discharge to rivers that occurred in the 1920s has declined as the depth to groundwater has increased. The winter flow of surface water to groundwater has declined along with the large winter flows.

Table 15. High-priority rivers and streams tributary to the Sacramento-San Joaquin Delta (DFG 2008).

Stream or Watercourse
American River
Antelope Creek
Battle Creek
Bear River
Big Chico Creek
Lower Butte Creek
Calaveras River
Cosumnes River
Cottonwood Creek
Cow Creek
Deer Creek
Lower Feather River
Merced River
Mokelumne River
Sacramento River, Keswick to Red Bluff
Lower San Joaquin River (below Merced R)
Upper San Joaquin River (above Merced R)
Stanislaus River
Tuolumne River
Yuba River

The California State Water Resources Control Board (2010) identified 28 river reaches and streams in the Sacramento-San Joaquin Delta watershed for which in-stream flow studies are required. Twenty of these are within the C2VSim model area (Table 15), including Butte Creek, the Lower American River and the Lower Merced River. Graphs of annual and monthly average groundwater discharges to these river reaches for the 1920s, 1960s and 2000s (Figure 94) show how the groundwater-river flow exchange has changed. Net annual groundwater discharges have declined for all three reaches, most dramatically on the American River where the flow direction has reversed. The monthly patterns of stream-aquifer flows for the three reaches have also changed over this time. The large seasonal differences on Butte Creek and the Merced River have been reduced. The nearly constant groundwater discharge on the American River has been replaced by a nearly constant flow of river water into the aquifer. These changes have impacted flow levels and water temperatures in these reaches, and may have also affected water chemistry.

Figure 92. Simulated stream-groundwater flows in California's Central Valley, 1922-2009

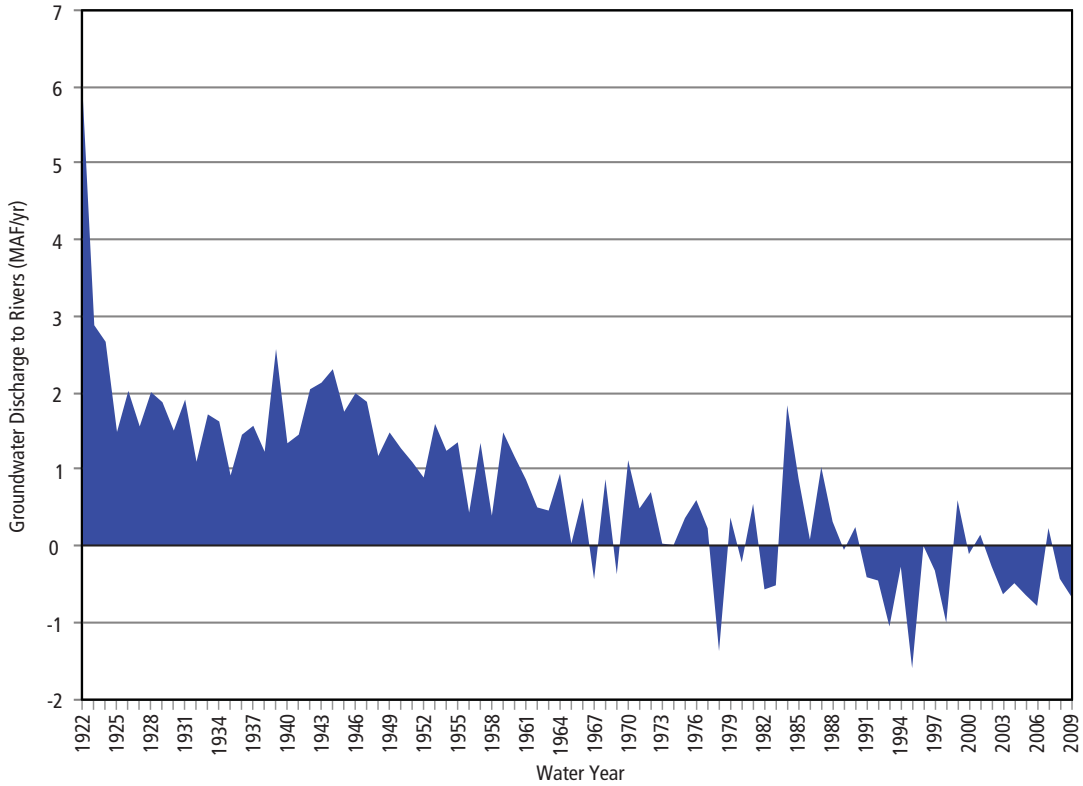


Figure 93. Simulated monthly stream-groundwater flows in California's Central Valley.

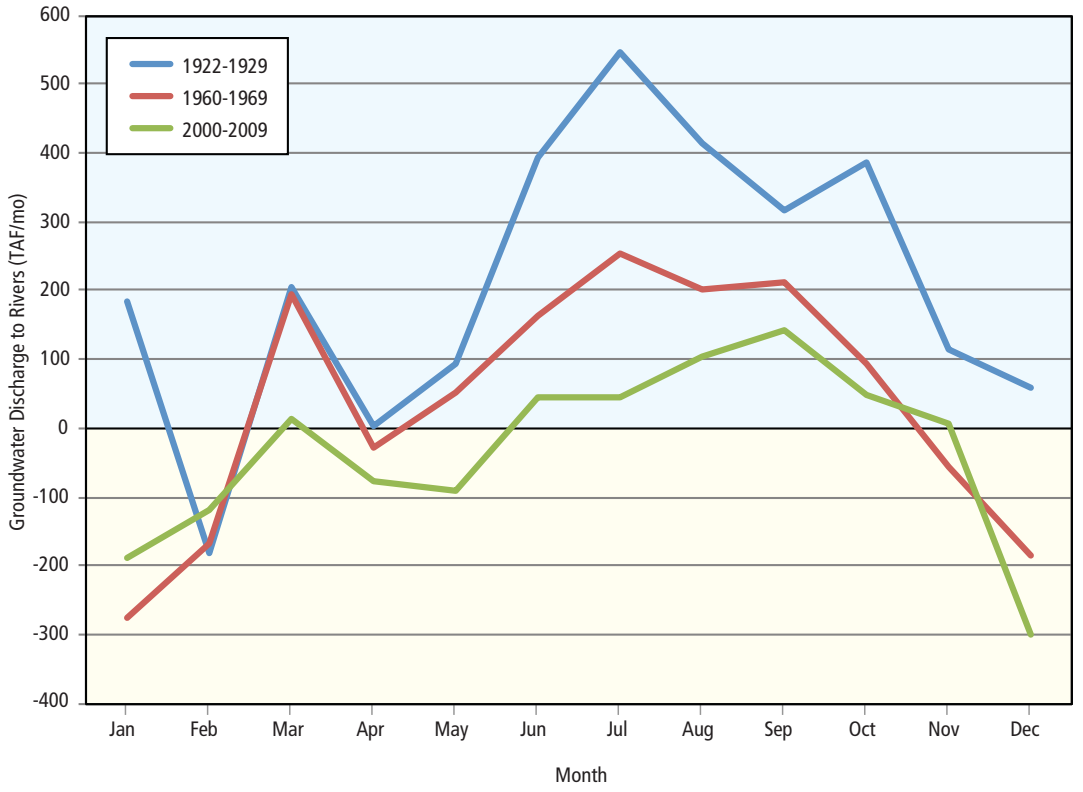
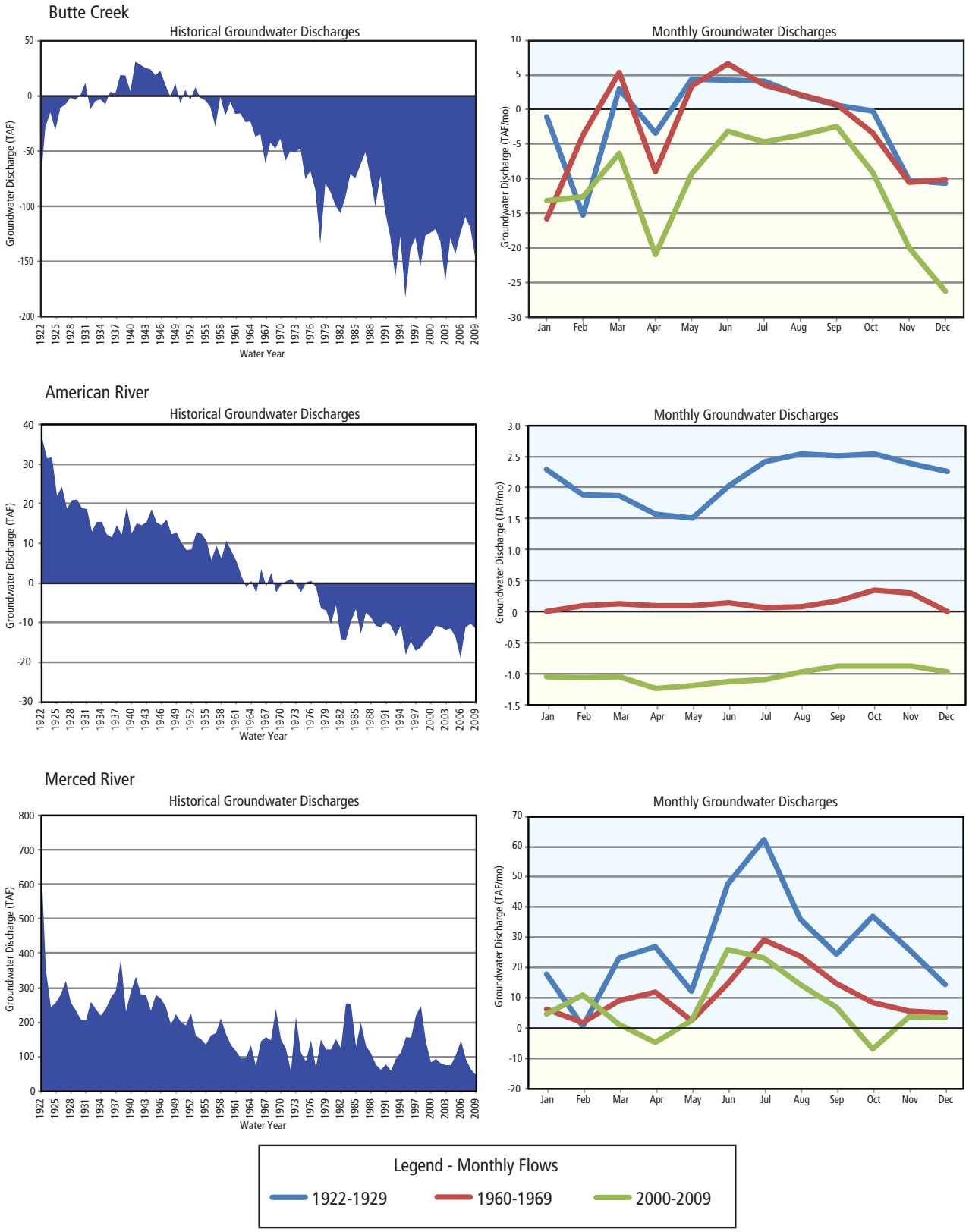


Figure 94. Simulated river-groundwater flows for selected river reaches.



Summary

The C2VSim model simulates the water flow through the interconnected land surface, surface water and groundwater flow systems of California's Central Valley on a monthly time step from October 1, 1921 through September 30, 2009. Model results provide detailed water budgets that show how changes in agricultural and urban land use, development of the surface water storage and distribution system and widespread groundwater pumping have altered the Central Valley's hydrologic system.

The C2VSim model is a comprehensive tool that can provide much of the information needed to understand how proposed management changes will affect the combined surface water and groundwater system of the Central Valley. This includes a comprehensive hydrogeologic framework; detailed water budgets listing the individual sources, sinks, and rates of recharge and discharge; and the ability to simulate the effects of past and current human activities and proposed future activities on the aquifer system.

Model Development

The C2VSim model is based on the finite element grid of the earlier CVGSM model (James M. Montgomery Consulting Engineers, 1990A and 1990B), which has 1,392 elements grouped into 21 water budget subregions. CVGSM data sets were modified to conform to the IWFM application format and were updated to simulate the period from October 1921 through September 2009, and numerous other improvements were made. Hydrologic parameters were calibrated to match observed groundwater heads, groundwater head differences between well pairs, surface water flows, and stream-groundwater flows for the period between September 1975 and October 2003, and land surface subsidence observations for the period between September 1957 and September 2004.

Central Valley Water Budgets

The C2VSim model produces several types of water budget tables, and this information can be summarized to produce water budgets for each model subregion, hydrologic regions comprised of several subregions, or the entire model area. Between 2000 and 2009, Central Valley river inflows varied between 17 and 54 MAF/yr of water, most originating as precipitation in upstream watersheds. Of the 32-42 MAF of water that passed through the Central Valley land surface each year between 2000 and 2009, roughly 26-30 MAF are on agricultural lands, 3-4 MAF/yr in urban areas, and 3-8 MAF/yr on native vegetation. Flows into and out of the Central Valley aquifer vary significantly regionally and from year to year, with high inflows from deep percolation recharge in wet years and high outflows to pumping in dry years. Groundwater pumping has generally been greater than inflows, resulting in reduced groundwater levels, groundwater storage and groundwater discharges to rivers, and in some areas to land surface subsidence.

Strengths and Limitations

The development of any regional model involves numerous decisions regarding model scale and accuracy. The C2VSim model was developed to use available data, run quickly, and produce regional water budgets. This was accomplished by using a fairly coarse finite element grid, a monthly time step, and water budget subregions based on historical land use data sets developed for previous DWR studies. Some of these decisions impose limitations on the use of C2VSim, which should be considered when the model is used in planning studies. The Central Valley has little topographic relief and a relatively deep water table, so the grid and subregion scales of the C2VSim model are adequate for calculating regional water budgets and their impacts on the groundwater and surface water (Kendy et al., 2003). Planned improvements to the C2VSim model will increase the spatial refinement of the model grid.

The C2VSim model uses a relatively coarse finite element grid, with an average cell area of 14.3 mi^2 (37 km^2 or 9123 acres). This grid was originally developed for the CVGSM model in the late 1980s when computers had less computational and storage capacity. This grid was retained in the C2VSim model in order to directly use many of the CVGSM data sets. Improvements to the numerical solver used in IWFM have significantly reduced model run times, and DWR is working to develop a more refined C2VSim grid.

The monthly time step matches the time discretization of much of the available historical hydrologic data, but may not capture all of the details of some water flow processes. Surface water diversion data in particular is generally only available with a monthly time step. A significant level of effort would be required to develop historical surface water diversion data for the entire Central Valley at a shorter time scale such as one day. Other input data, such as precipitation, evapotranspiration and river inflow rates, are available on a daily time step. The monthly time step is adequate for the purposes of generating regional water budgets for the Central Valley.

Many land surface and root zone water budget components are calculated for each subregion and land use type in the IWFM version (3.02) used by the C2VSim model. These flow components are allocated from the subregion to model elements based on the proportion of the subregional land use area in each element. For example, if a model element has 1% of the subregion agricultural area and 3% of the subregion urban area, then the deep percolation from the element will be equal to 1% of the subregion agricultural deep percolation plus 3% of the subregion urban deep percolation. This method allows rapid calculation of subregion water budgets using available data, but produces a very homogeneous deep percolation profile across each subregion. This limits the ability of the model to match the natural heterogeneity that exists within each subregion. This limitation has been addressed in IWFM version 4.0, which allows land surface and root zone process flow terms to be calculated for each model element. However, historical crop acreages must be specified for each model element to use this functionality, and this may require a significant level of effort.

The river flow process in IWFM version 3.02 does not incorporate storage changes on river segments. The outflow from each river segment in each time step is equal to the inflows to that segment. In the Central Valley, the longest residence time to pass through the river system is several days, much less than the monthly simulation time step. Thus omitting storage from the river flow system simulation is justified for the C2VSim model. This simplification ignores the small changes in storage that occur as river levels rise and fall throughout the season, but this amount is negligible in comparison to the amount of water flowing through the river system.

The C2VSim model calculates monthly groundwater pumping rates for each subregion to meet residual agricultural and urban water demands after accounting for infiltrated precipitation and surface water deliveries. These groundwater pumping estimates are very sensitive to the crop evapotranspiration rates and crop acreages. The IWFM Land Surface Process calculates a water budget for each land use in each subregion, balancing outflows (to evapotranspiration and deep percolation) against inflows (from infiltrated precipitation, infiltrated irrigation water, from surface water diversions and groundwater pumping), and the change in root-zone moisture storage. The Land Surface Process adjusts the groundwater pumping volume (and thus the corresponding infiltration) upward or downward until the inflows and outflows are exactly equal. A small increase or decrease in the evapotranspiration rate or crop acreage will change the total agricultural water demand, and thus directly influence the calculated groundwater pumping rate. Robust groundwater pumping estimates are therefore dependent on reliable crop acreage, precipitation, surface water diversion and evapotranspiration data.

A number of parameters are used in the C2VSim model to specify water management practices. These parameters are fixed throughout the model simulation, but may in fact have changed through time as water management practices evolved. For example, a recoverable loss factor representing canal seepage is specified for each surface water diversion. The recoverable loss factor for a specific canal may have changed during the 88-year simulation period, perhaps decreasing when a canal was lined or increasing as a canal lining aged and developed cracks. Another input parameter, basin irrigation efficiency, was also fixed throughout the simulation period; model results may not be as sensitive to this parameter because although irrigation efficiencies in the Central Valley have improved over time, growers most likely used the extra available water to increase crop production (Hanson and May, 2006). Historical values for many water management parameters are not available.

The aquifer parameters in the C2VSim model are regional values determined through model calibration to match heads, head differences and average stream-groundwater flows. These parameter values preserve the observed mean water flux through the heterogeneous aquifer materials under the range of observed head gradients (Zhang et al., 2010) at the coarse scale of the finite element grid. The last hydrogeologic synthesis of the Central Valley aquifer (summarized by Bertoldi et al., 1991) was completed more than 20 years ago, and was based on information gathered from the 1950s to early 1980s. Many advancements in scientific methods

have occurred since then, and many local studies have added new information and understanding about the Central Valley aquifer. For example, several concepts that were not understood at that time are (a) rates of tectonic subsidence, (b) the effect of conjunctive use on stream flows, (c) the role of local aquifer discharges in maintaining flows for anadromous and other species, and (d) aquifer contamination with nitrates from agricultural fertilizers via deep percolation. A hydrogeological synthesis for the Central Valley would add significant understanding and aid groundwater management.

Future Work

The C2VSim model described in this report uses a relatively coarse finite element grid and a monthly time step, and is run with IWFM version 3.02, which uses subregional land use and crop data. A C2VSim version utilizing a refined finite element mesh is currently under development. IWFM version 4.0, which supports elemental water budget calculations, was recently released by DWR (Dogrul, 2012E and 2012F). A C2VSim version using IWFM version 4.0 would require development of element-level input data sets, although some of the required data is already available from the SIMETAW-II model (Snyder et al., 2009).

Applications

A preliminary version of the C2VSim model was used for several hydrologic studies. These studies helped identify areas where the model could be improved. The groundwater component of the C2VSim model is also currently being used in the CalSim 3 water resources simulation model to represent the groundwater and stream-aquifer flow dynamics. DWR staff collaborated with researchers at Lawrence Berkeley National Laboratory to study how the Central Valley aquifers might be impacted by an extended drought (Miller et al., 2009). C2VSim was also used to investigate the effects of a proposed groundwater substitution water transfer project in the Sacramento Valley on river-aquifer flows.

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