Supplementary Materials for Groundwater Sustainability and Subsidence in California's Central Valley

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All elevation data are relative to the National Geodetic Vertical Datum of 1929 (NGVD29).

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Supplementary Materials

The supplementary information describes the updates to the Central Valley Hydrologic Model (CVHM) [5]. CVHM version 1 (CVHM1) is fully documented and archived [5]. This updated model is referred to as CVHM version 2 (CVHM2) and supersedes CVHM1. The datasets used in CVHM2 are released and documented [29,33,43–49]. The updated CVHM2 model files are provided in [45,59]. The updated CVHM2 includes the original water year (WY) 1962 to WY 2003 simulation period and extends the end of the simulation period from WY 2003 to WY 2019. The CVHM2 model layers are increased from 10 layers to 13 layers, the texture model is updated to include new information, and aquifer properties are assigned with more detail [33,44,45]. Many new processes were included in the updated model, most notably delayed subsidence, small watershed flows, inter-borehole flow for all wells, and water-banking recharge [43,47–49]. The model was recalibrated to existing, extended, and new datasets [46]. The supplementary materials document this update and are broken into three main sections: (S1) input data, (S2) model development, and (S3) model calibration.

(S1) Input Data

The updated datasets used in CVHM2 are documented in a series of data releases [29,33,43–49]. This supplementary materials document adds additional details to selected datasets that required extensive pre-processing and analysis before the data could be used as model input, beyond what is documented in the data releases. This section especially focuses on the details of datasets that were updated from CVHM1.

Water Balance Subregions (WBSs)

The 21 water-balance subregions (WBSs) defined in CVHM1 [5] and the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim) [38] are refined spatially to 135 WBSs in CVHM2 [45] (fig. S1). The resolutions of the WBSs change temporarily during the model simulation as more detailed data become available to support higher resolutions for the WBSs. To prevent confusion, the 135 WBSs in CVHM2 may also be referred to as "farms" to be consistent with CVHM1 terminology. Similar to CVHM1, the 135 WBSs are aggregated to the 21 regions for analysis in CVHM2, and sometimes the WBSs are further aggregated to 4 regions referred to as the Sacramento region, Delta-Eastside Streams region, San Joaquin Basin region, and Tulare Basin region (fig. 1 in main article).

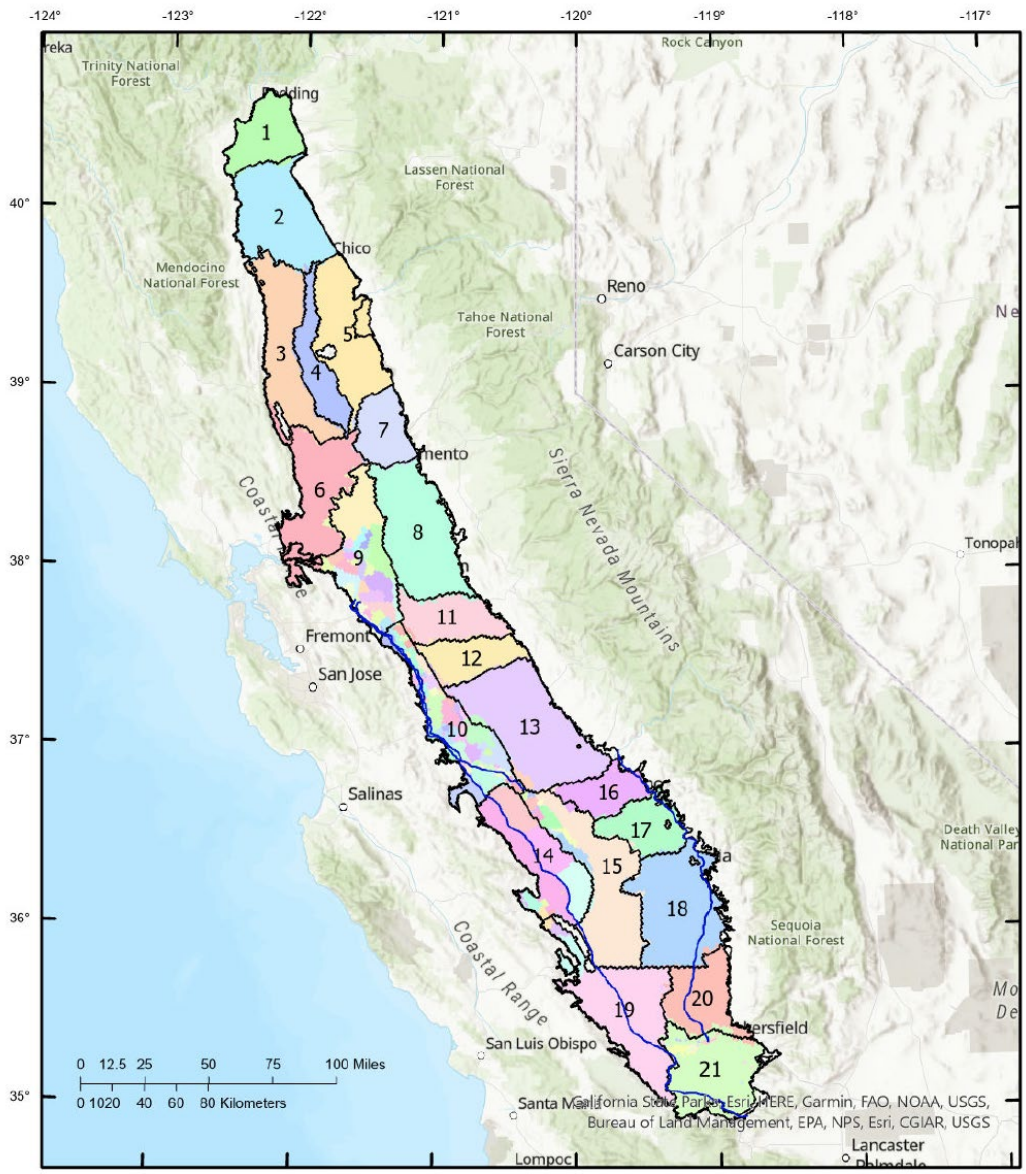


Figure S1. The Central Valley Hydrologic Model version 2 (CVHM2) [1] includes 135 water balance subregions (WBSs) [45] that are shaded in various colors. The 21 water balance subregions (WBSs) defined in CVHM1 [5] are overlain on these WBSs and outlined in black.

Surface-Water Inflows and Bypasses

CVHM1 simulates 44 gaged streams that flow into the Central Valley [5]. CVHM2 expands upon the original gaged flow by including surface-water inflow defined in [38,41] and includes 65 new surface-water inflow locations [44]. Several of these additional inflow locations replace and refine

CVHM1 inflow sites. Data for eight inflow locations along the west side of the San Joaquin Valley were added to better simulate inflows in the western San Joaquin Valley. The new inflows include Los Gatos Creek, Del Puerto Creek, Cantua Creek, Hospital Creek, Los Banos Creek, Little Panoche Creek, Panoche Creek, and Ingram Creek [44]. CVHM2 simulates 13 major flood control bypasses and bifurcations in the Central Valley, including six bypasses on the Sacramento River system (Moulton, Colusa, Tisdale, and Fremont weirs, Sacramento Weir, and Knights Landing Ridge Cut), three bypasses on the San Joaquin River system (Chowchilla bypass, Eastside Bypass, and Mariposa Bypass), and one bypass on the Kings River system (Fresno Slough/James Bypass).

Managed Aquifer Recharge

Managed aquifer recharge (MAR) is a water-management strategy that strives to store excess surface water when it is available and used to meet water demands during dry periods, or periods of high-water demand, when surface-water supplies are low [90,91]. In the Central Valley, MAR primarily is done through surface-water impoundments in the southern part of the Central Valley in Fresno and Kern Counties (fig. S2). Fresno County recharges water from the San Joaquin and Kings Rivers; Kern County uses water from the Kern River, the Governor Edmund G Brown California Aqueduct (hereafter referred to as the "California Aqueduct"), and the Friant–Kern Canal. Data were compiled for 10 MAR programs that include facilities by the City of Fresno in Fresno County, and nine other operations in Kern County: Berrenda Mesa Property Joint Water Banking Project, City of Bakersfield 2800 Acre Groundwater Recharge Facility, Kern Water Bank, Pioneer Groundwater Recharge and Recovery Project (renamed the Thomas N. Clark Recharge and Banking Project in 2010), City of Bakersfield recharge in the Kern River Channel, Buena Vista Water Storage District/West Kern Water District Water Supply Project, Rosedale-Rio Bravo Water Storage District’s Groundwater Banking Program, Semitropic Groundwater Banking Project (which includes the Poso Creek Integrated Regional Water

Management (IRWM) Group), and Arvin–Edison Water Storage District Water Management Program [43]. Although CVHM2 simulations run through 2019, data from 2014-2019 were not available during development of CVHM2, so water-year indexes were used and applied to all ten MAR programs to extend data for the 2014-2019 period [43].

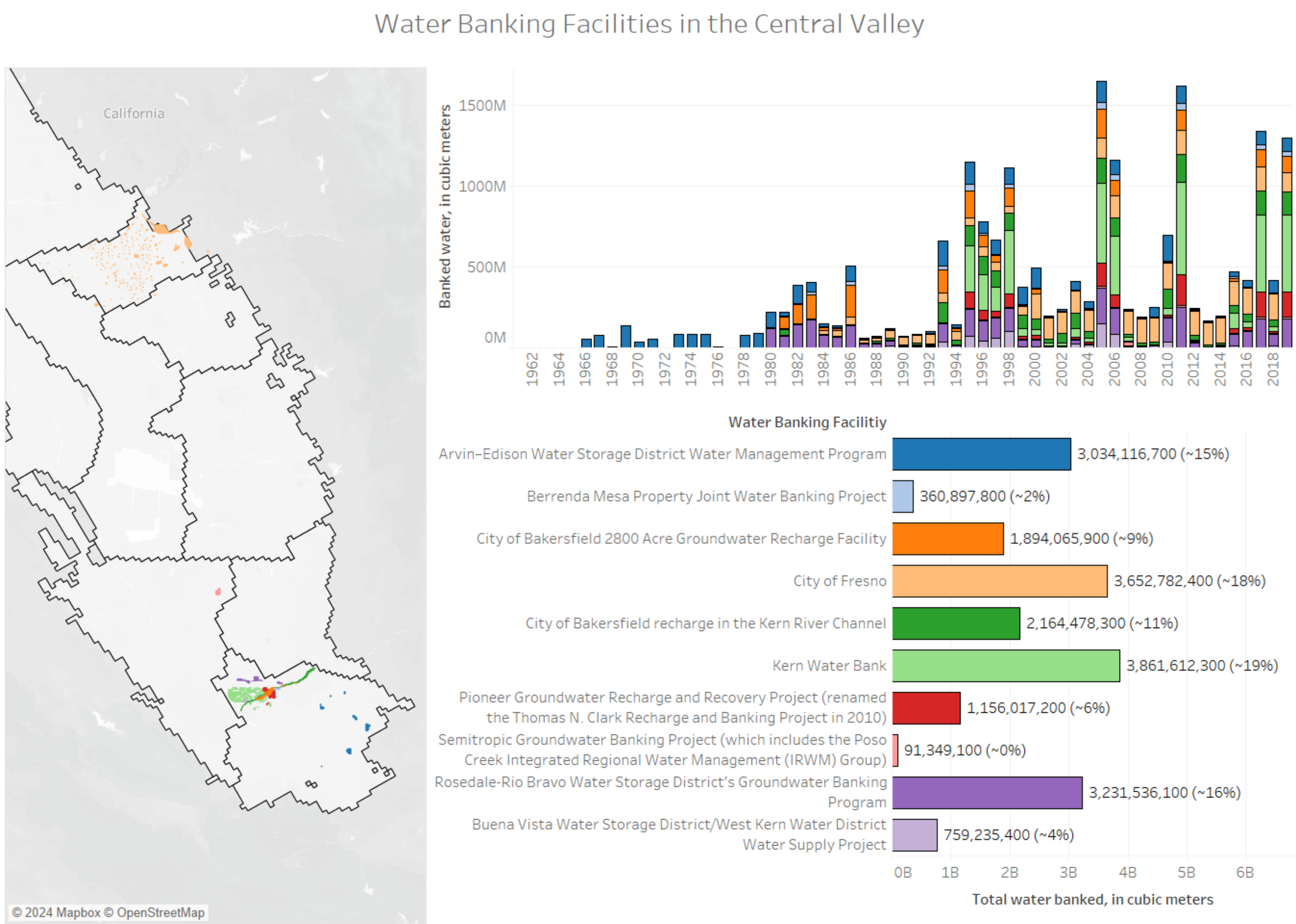


Figure S2. Map of water-banking facilities, Central Valley, California, and graph showing recharge at Managed Aquifer Recharge (MAR) facilities in CVHM2 [43].

Diversions

In CVHM2, the surface-water diversions were updated from CVHM1 to include additional data sources:

- Diversions from C2VSim [38,41],

- Diversions from WestSim [92],
- Delta turnout diversion data [93],
- Delta-Mendota Canal delivery data (written communication, Bob Martin, San Luis – Delta Mendota Water Authority, 2014).

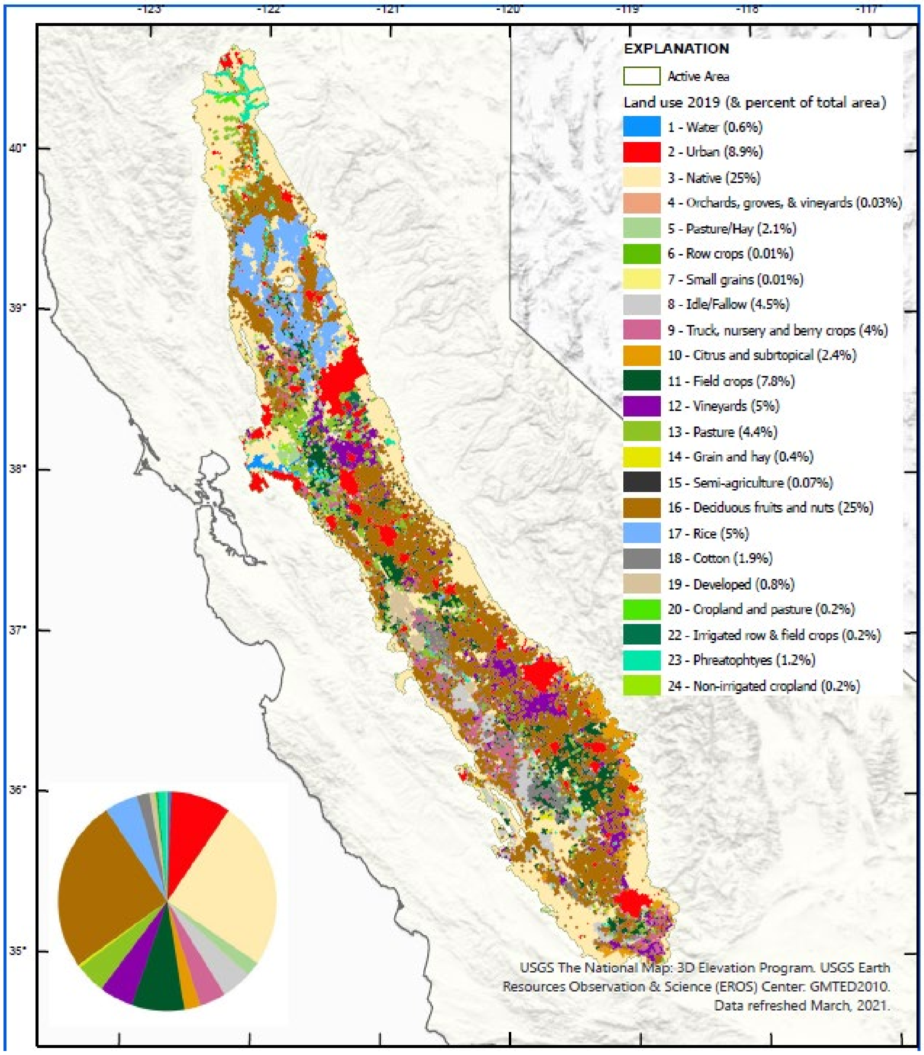
Detailed information on these sources of data used to develop the diversion input dataset for the CVHM2 and on the processing methods used to combine and convert the raw data are documented in the diversion data release [44].

Tile Drainage

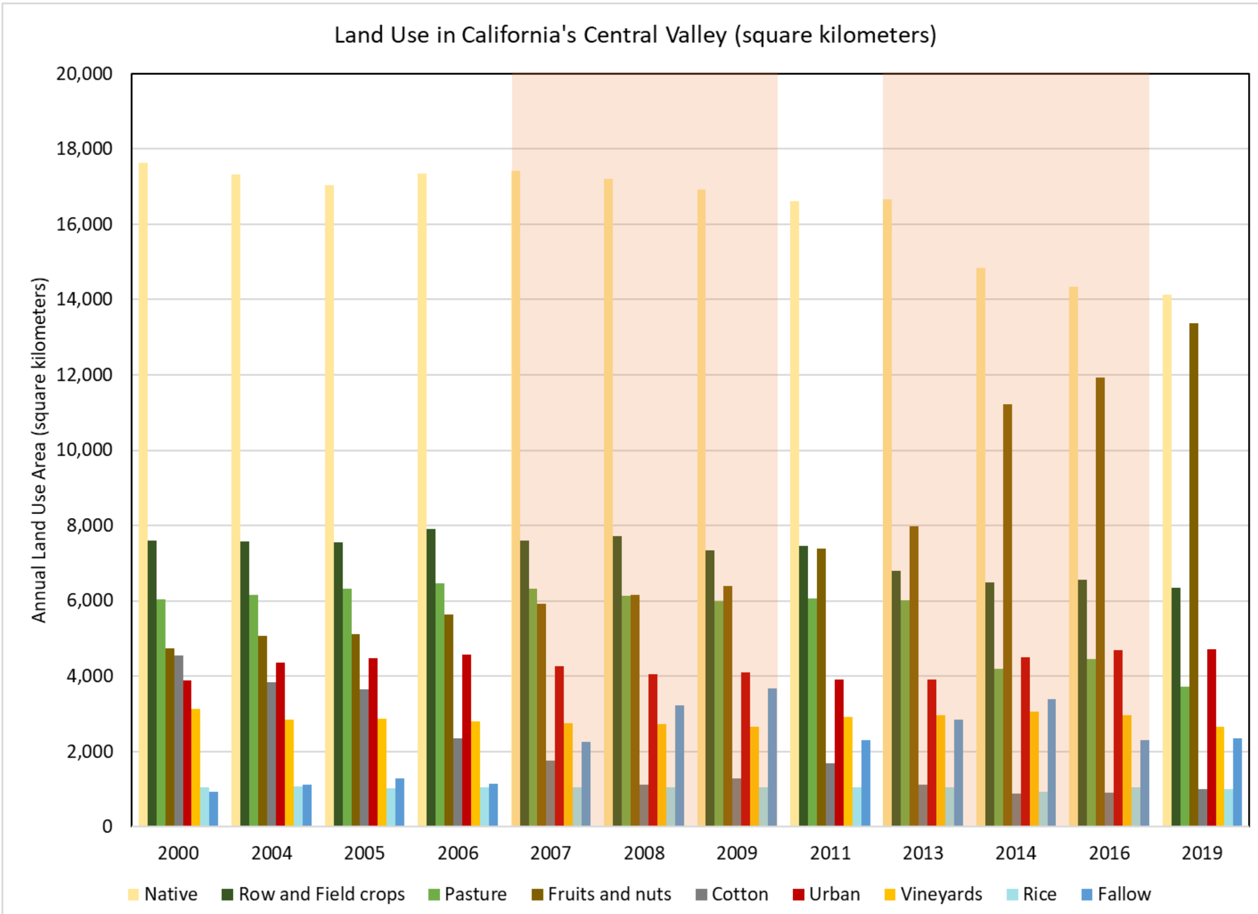
CVHM1 did not simulate tile drain discharge in the west side of the San Joaquin Valley. Upgrades in CVHM2 include simulations of on-farm drains in WBSs 89, 90, 91, 93, 94, 97, 99, 100, and 101 and regional drains in WBSs 102 and 108. The data for the drain flow and locations are taken from WestSim [44].

Land-Use Data

CVHM1 incorporated land-use data from 1961-2003 [5]. These datasets were grouped into urban, native, and agricultural classes as described in 2003 [5] resulting in 22 classes loosely based on the 12 CDWR class-1 categories [2,94]. In addition to the 22 land-use classes used in CVHM1, CVHM2 added two additional classes: phreatophytes and non-irrigated cropland [29] (fig. S3). CVHM2 uses the same methodology for estimating unknown land-use changes as CVHM1 [5]. This method linearly "morphs" the land-use area between two known land-use area maps on an annual basis. Periods between known, or documented, land-use data and maps ranged from decades in the early part of the model, to annual in some counties in the last 14 years of the simulation. The land-use map from 2019 shows agriculture covers approximately 64 percent of the valley, native vegetation, water and phreatophytes cover about 27 percent, and urban land use covers almost 9 percent (fig. S3).



(a)



(b)

Figure S3. (a) Land uses for 2019 for California's Central Valley [29], which were largely based on California Department of Water Resources class-1 land-use categories [2] and general classes developed by [5]. Twenty-four land-use classes are used in the CVHM2, including two new classes: phreatophytes and non-irrigated cropland [29] (b) Land use for available water years 2000-2019 for California's Central Valley [29]. Water years classified as below normal, dry, or critical for Sacramento Valley and San Joaquin Valley are shaded [95].

Land-Subsidence Data

The incorporation of a diverse and comprehensive set of land-subsidence data is a major enhancement to CVHM2. Several methods are available to monitor land subsidence in the Central Valley. The most basic approaches compare repeat regional-scale differential surveys that measure relative changes in the position of the land surface over time [21]. These surveys measure the position of geodetic monuments, or benchmarks, installed on artificial foundations or on rods driven to depth using conventional spirit leveling [96]. Since the advent of portable Global Positioning System (GPS) antenna/receivers in the early 1990s, spirit leveling has largely been supplanted by campaign GPS surveys and continuous GPS (CGPS) surveys. Vertical borehole extensometers can also be used to monitor changes in the distance between the top of a cable or pipe that is anchored or placed at depth and a reference point at or near land surface [97,98]. This change in distance represents the aquifer compaction between the bottom of the borehole and the reference point. Interferometric Synthetic Aperture Radar (InSAR), one of the latest tools used to measure subsidence, uses radar signals from satellite or airborne platforms to measure deformation of the Earth's land surface at high resolution [21].

Geodetic Surveys

The term geodetic survey includes spirit leveling and campaign GPS surveys. Spirit leveling and campaign GPS surveys can be used separately or conjunctively during a single geodetic survey. Both survey types use benchmarks and involve collection of similar numbers of measurements through space and time [19], In some cases, GPS surveys have supplanted spirit-leveling surveys [99,100].

A spirit-leveling survey, also called a differential-leveling survey, is the oldest method used to precisely measure elevation. Spirit-leveling surveys that were used during the development of CVHM2 were completed along linear infrastructures including roads, railroad tracks, aqueducts, and canals as part of initial construction or ongoing maintenance. The first subsidence contour maps in the San Joaquin Valley were constructed by comparing results of spirit-leveling surveys to topographic maps [79]. Despite its age and simplicity, this method can still be used to achieve the most accurate elevation measurements of all the methods described. Geodetic surveys in the Central Valley often use benchmarks that are on the order of about 45 m or less apart, which for long features such as the California Aqueduct (approximately 1,125-km in length), can generate thousands of observations of subsidence. Unfortunately, these surveys are only available in specific locations in the Central Valley, such as along the Delta-Mendota Canal and along the California Aqueduct.

The GPS is a United States owned utility that provides users with positioning, navigation, and timing services, and is part of the Global Navigation Satellite System (GNSS). Users can obtain elevations at specific locations autonomously rather than relying on an elevation from a known reference point to use as a datum for other points. However, users often link surveys to several CGPS sites to align their surveys with the global reference frame [101]. Like spirit leveling, repeated surveys of the same points over time produce a time series of elevation data from which changes in elevation are calculated. Using the procedures outlined by the National Geodetic Survey (NGS), GPS surveys can be used to achieve accurate horizontal positions (typically ± 6 millimeters) and fairly accurate vertical positions (typically ± 2 cm; [102]. Published and unpublished data from previously completed geodetic surveys in the Central Valley done by the U.S. Geological Survey (USGS), the Bureau of Reclamation, California Department of Water Resources (CDWR), NGS, and San Luis and Delta-Mendota Water Authority (SLDMWA) were obtained and used as subsidence observations [46]. The data include subsidence observations derived from regional surveys and from linear surveys along water conveyance and transportation alignments.

Table S1. Summary of geodetic surveys used for CVHM2 model calibration, Central Valley, California. [USGS, U.S. Geological Survey; SLDMWA, San Luis and Delta-Mendota Water Authority; Reclamation, Bureau of Reclamation; NGS, National Geodetic Survey]

Area	Number of locations	Data Availability	Source Agency	Published Source
San Joaquin Valley	39	1926–70	USGS	Ireland and others, 1984
Sacramento Valley	11	1926–70	USGS	Assumed no subsidence

Delta-Mendota Canal	119	1935–2016	Reclamation SLDMWA	Bob Martin, San Luis and Delta-Mendota Water Authority, written commun., 2012; [103]
Friant-Kern Canal	11	1948–2017	Reclamation	[103]
California Aqueduct	317	1960s–2017	CDWR	Forrest Smith, California Department of Water Resources, written commun., 2009; Daniel Mardock, California Department of Water Resources, written commun., 2018
Hwy 198	14	1960s–2004	NGS	Marti Ikehara, National Geodetic Survey, written commun., 2012; National Geodetic Survey archives
Hwy 152	23	1972–2004	NGS	Marti Ikehara, National Geodetic Survey, written commun., 2012; National Geodetic Survey archives
San Joaquin Valley	73	2011–17	Reclamation	[103]

Borehole Extensometers

A borehole extensometer is used to measure the one-dimensional (1-D) thickness of a specified depth interval of an aquifer system. A borehole extensometer is often described as a deep benchmark, and the distance between the deep benchmark (bottom of the extensometer) and some reference point on or near the Earth's surface is the measurement that is made. When the distance shortens, aquifer-system compaction occurred, and when the distance lengthens, expansion occurred.

Aquifer-system compaction data from 23 selected borehole extensometers— 3 from Sacramento Valley and 20 from the San Joaquin Valley [46] — were assembled from various sources. Where possible, data were combined to form temporally dense and long-term compaction histories. The data varied in format, precision, and temporal density and included manual readings of measuring tapes or dial gages obtained from field notes, published and unpublished annual compaction totals, and electronic compaction measurements. These temporally dense datasets were then reconciled with available published annual compaction magnitudes [84]. Some adjustments to and assumptions about the data were necessary during the process of combining the data from the different sources or for the reconciliation, including omitting compaction measurements prior to the published start of the record (presumably during initial calibration and testing), considering the effects of friction-release procedures (manual oscillations) and other equipment adjustments during field visits, and assuming no compaction occurred when there were data gaps that could not be bridged.

Continuous Global Positioning System (CGPS)

A Continuous Global Positioning System (CGPS) site continuously measures the three-dimensional (3-D) position of a point on or near the Earth's surface. There is a network of more than 1,000 CGPS sites in western North America [104] that are operated by various scientific research consortiums or other groups. Much of the network is managed and processed by the Geodetic Facility for the Advancement of Geoscience (GAGE), which was previous part of the Plate Boundary Observatory (PBO) [105] and is one of the National Science Foundation’s two premier geophysical facilities. The CGPS sites generally were constructed to monitor motions caused by plate tectonics but can be used for other applications including subsidence monitoring. There are about 40 CGPS sites located within the Central Valley that have been operating since as early as 1999, although most were installed during 2005–2006. The CGPS sites are like the portable GPS systems previously described, but the user segment consists of a receiver/antenna system designed to last for many years rather than a temporarily installed antenna/receiver system. These CGPS sites generally collect 3-D position information every 15 seconds which are then processed to produce a daily position [104]. The temporal resolution of CGPS is the highest of all subsidence monitoring methods, which facilitates detailed time-series analyses, but the limited spatial density and relatively short history prevent regional and longer term (decadal) subsidence analyses without the integration of measurements derived from other monitoring methods.

Data for 40 CGPS sites completed in the alluvium of the Central Valley (13 in the Sacramento Valley and 27 in the San Joaquin Valley) that are part of the GAGE were used as subsidence observations for model calibration [46,106]. Daily CGPS position time-series data were downloaded from the PBO website [106] using the North American Tectonic Plate reference frame. Day-to-day CGPS height solutions at these sites varied by as much as 3.6 cm likely due to variable atmospheric conditions, random walk noise, and other effects not directly related to land-surface-elevation change [107–109]. To minimize this high-frequency noise, a 31-day moving average was applied to the CGPS data. The removal of the day-to-day variations in CGPS heights minimized high-frequency variations without removing seasonal or long-term deformation trends that are needed for CVHM2 observations (fig. S4). CGPS records are typically available at a daily or even hourly frequency, but for this study a monthly average subsidence value was calculated to coincide with the monthly stress periods of CVHM2.

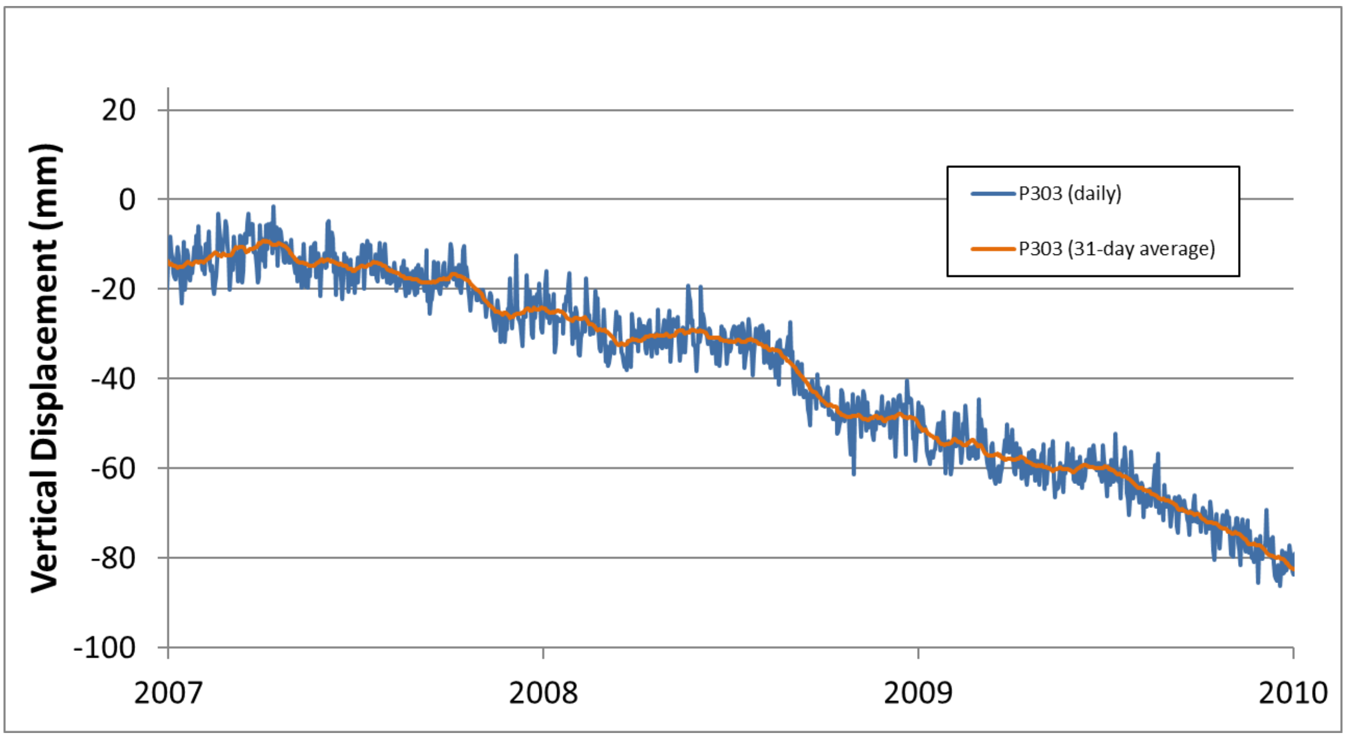


Figure S4. Daily and averaged (31-day moving) continuous Global Positioning System (CGPS) data from site P303, near Los Banos, San Joaquin Valley, California. Data and location of P303 are provided in [46].

Interferometric Synthetic Aperture Radar

Interferometric Synthetic Aperture Radar (InSAR) is a satellite or airborne-based remote sensing technique that can detect centimeter level ground-surface deformation over hundreds of square kilometers at a spatial resolution (pixel size) of 90 m or smaller [110]. The high spatial resolutions of InSAR data are ideally suited to measure the spatial extent and magnitude of surface deformation associated with fluid extraction (groundwater). For this study, 32 interferograms were processed using satellite SAR data collected between July 2003 and July 2010 [111], and 26 interferograms were processed using uninhabited aerial vehicle synthetic aperature radar (UAVSAR) data collected between 2013 and 2016 [112]. These data were used to construct subsidence observation time series datasets in the San Joaquin Valley [46]. InSAR time-series datasets were compiled for 38 locations distributed throughout the San Joaquin Valley, and UAVSAR time-series datasets were compiled for 206 locations along the California Aqueduct. Locations were selected based on subsidence magnitude, spatial distribution, and availability of other measurements.

(S2) Model Development

This section introduces the simulation code and describes updates and changes to CVHM1. The description focuses on how the datasets described in (S1) were used in CVHM2. The simulation code used in CVHM2 is MODFLOW-One-Water Hydrologic Flow Model version 2.3 (OWHM), which is fully documented in [52,53]. OWHM incorporates and uses the MODFLOW-2005 which is documented in [50]. CVHM2 heavily leverages the new input style documented in Appendix 1 and 2 of [53].

A list of all the packages and processes used in CVHM2 is in the CVHM2 model release [59]. CVHM2 also uses several feed files to input much of the time-series data in the model. Feed files are associated with each package or process. CVHM2 also used two-dimensional (2-D) arrays for much of its input data. Updates to the Streamflow Routing, Farm Process (FMP), and Subsidence Package have their own sections because these updates were more extensive.

Model Discretization

CVHM2 uses the same basic spatial and temporal discretization as was used in CVHM1. Spatially, CVHM2 still uses 1.6-km by 1.6-km cells in the horizontal direction. Vertically, CVHM2 is now composed of 13 layers compared to the 10 in CVHM1. The upper three layers from CVHM1 are split into five layers, the Corcoran Clay Member of Tulare Formation (hereafter "Corcoran Clay") that was previously simulated as two layers is now split into three layers, and the lowest 5 layers of CVHM2 correspond to the original lowest five layers in CVHM1. The top and bottom elevations of these new layers are documented in CVHM2 Model Setup Files data release [45]. Temporally, CVHM2 simulates monthly stress periods with two equal length time steps similar to CVHM1. The simulation period for CVHM2 has been extended from water year (WY) 1962 to WY 2019. A water year is the one-year period from October 1st through the following September 30th and is named for the calendar year at the end of the period.

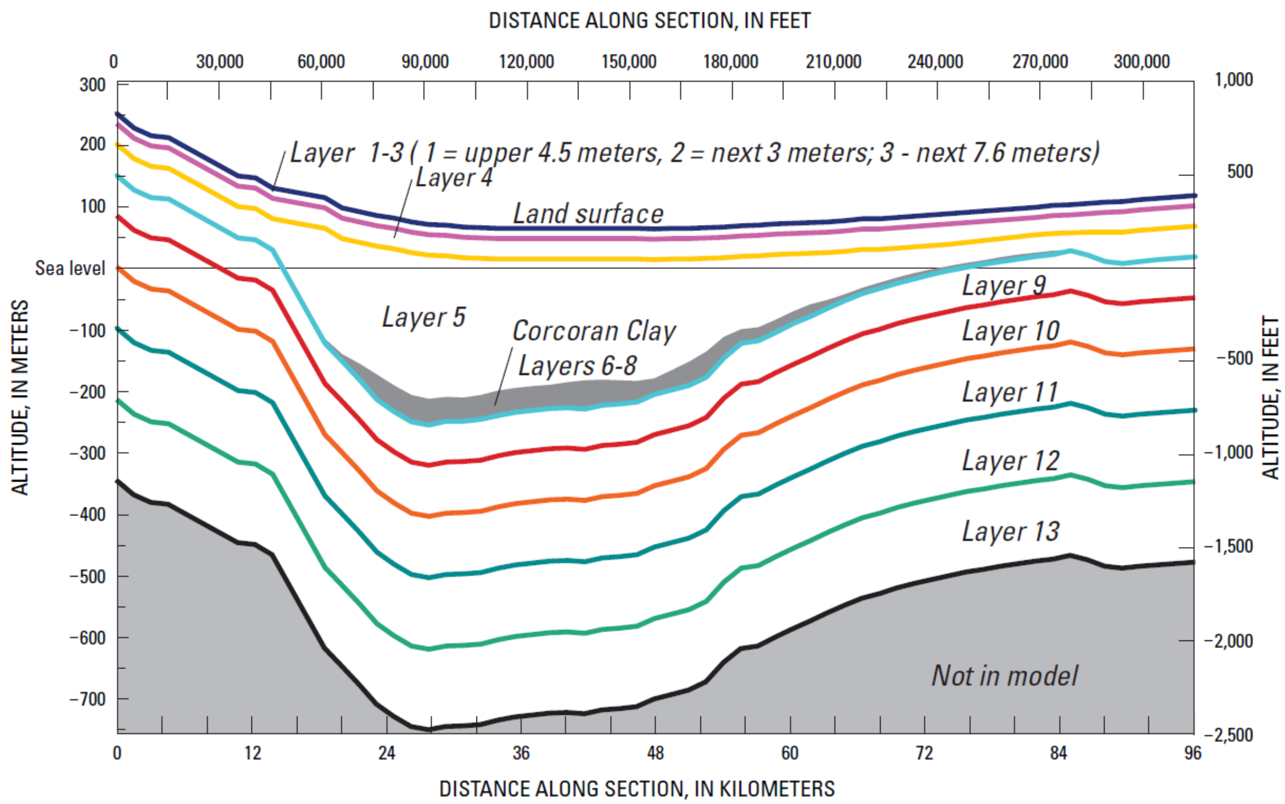


Figure S5. Generalized hydrogeologic section indicating the vertical discretization of the Central Valley Hydrologic Model version 2 (CVHM2) of the groundwater-flow system in the Central Valley, California. Line of section along row 355.

Cells in CVHM2 are organized into accounting units termed WBSs. These WBSs are used to define many of the farm-process model inputs and produce output budgets. In CVHM1, WBSs definitions were fixed for the entire simulation, but in CVHM2, these WBSs change through time to match the increased resolution of available datasets. For input, the WBSs are defined for each stress period and become more detailed later in the model simulation time allowing the incorporation of more detailed input datasets that only become available later in time. The number of WBSs increases up to a maximum of 135. Irrigation water service areas are represented by 122 of these WBSs, and the other 13 WBSs represented MAR areas. WBS 136 (located in the inactive cell row 1, column 1) is used as a means for exporting surface water out of the CVHM2 model. These WBSs are documented in CVHM2 Model Setup Files data release [45].

Like CVHM1, hydraulic properties were based on a percentage of coarse-grained deposits. The percentage coarse-grained deposit is used in the MULT file [50,52,53] to define hydraulic properties that are used in the UPW [50,52,53] and SUB [51–53] packages. The well logs database, percentage of coarse-grained deposits, and layer tops and extents are documented by [33]. Additional geologic zones were defined to represent: (1) the Corcoran Clay (represented by portions of layers 6-8) and (2) the geologic formations at the margins of the Central Valley referred to in previous reports as dissected uplands [5,45].

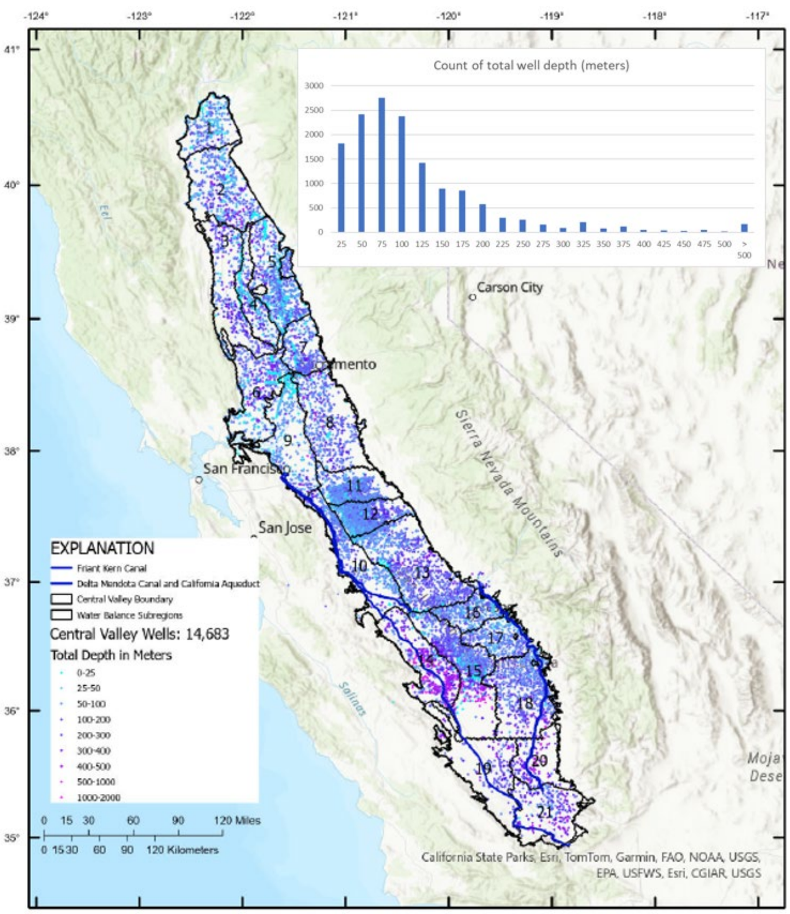


Figure S6. Central Valley drillers' logs used in the CVHM2 texture model and total depth of lithology available at each well [33].

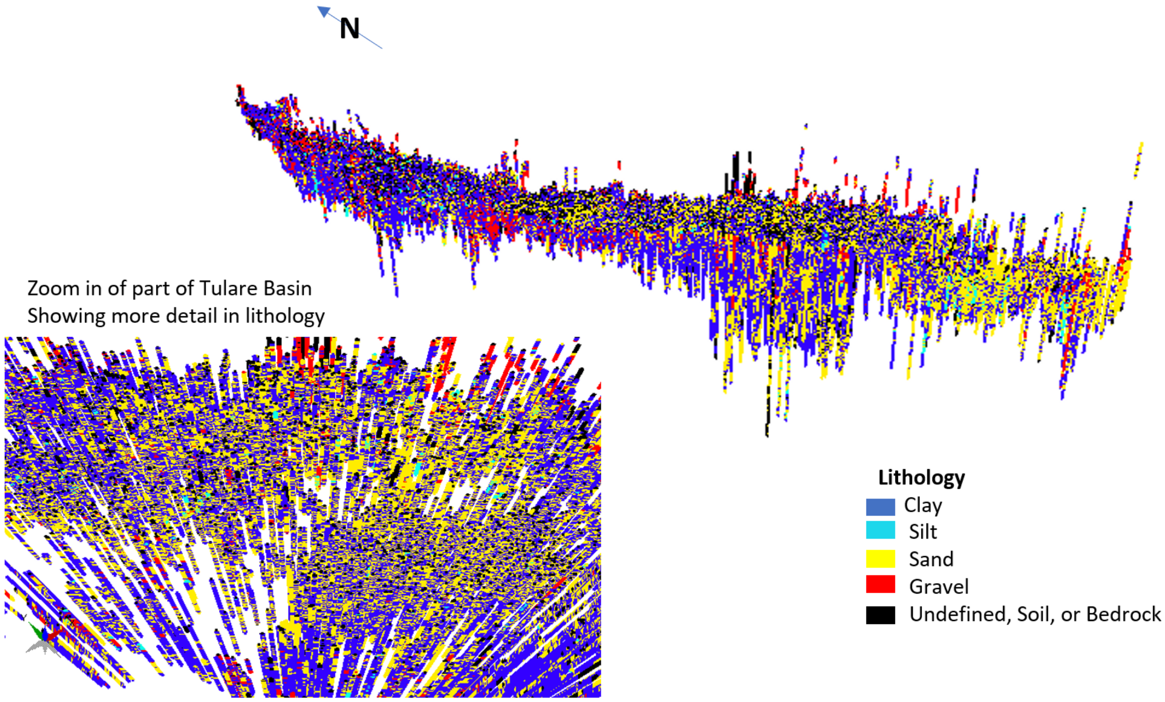


Figure S7. Central Valley drillers' logs in three-dimensional space coded with lithology [33].

Boundary Conditions

CVHM2 initially used the same starting heads as CVHM1. At the beginning and periodically throughout model calibration, the model was cycled for 24 stress periods to allow the groundwater solution to equilibrate with the model hydraulic properties and boundary conditions and diminish associated spurious transient conditions caused by specified initial heads. Groundwater flow to and from the Sacramento-San Joaquin Delta (hereafter referred to as "the Delta") was enhanced in CVHM2 to consider the general rise in sea level from WY 1962 to WY 2019. The general head boundary flow package was used to simulate these net groundwater inflows and outflows through model boundaries. These tidal data are documented in CVHM2 Model Setup Files data release [45].

Tile drainage was not simulated in the original CVHM1. CVHM2 was upgraded to simulate on-farm tile drains in the west side of the San Joaquin Valley. The Drain Return package was used with the new RETURNFLOW option (documented in Appendix 3 of [53]), which allows the simulated drain flows to “pass through” the FMP and then be returned to the simulated stream network in the same way that the FMP handles runoff from agriculture. The observation magnitude and locations of the simulated drains are documented by [45].

Four categories of groundwater pumping are simulated in CVHM2, including municipal, rural, recovery, and agriculture (compared to just agriculture and urban in CVHM1). The well locations, well properties, and pumping rates for each of these pumping categories are documented by [45]. Municipal and rural pumping rates were estimated using population and water-use factors, and the step-by-step calculation methodology is documented in [49]. The recovery pumping represents the pumping/recovery operations of MAR operations, where known. Agricultural pumping rates are estimated in CVHM2 by the FMP.

In CVHM1, pumping wells were simulated as virtual wells [5]. CVHM2 still uses this assumption for agricultural, rural, and recovery wells; however, municipal wells are located as documented, and pumping is applied to the finite difference cell center in MODFLOW. Multi-node wells [54,55] were used in CVHM1 to represent wells crossing the Corcoran Clay, where interborehole flow is more substantial [5]. In CVHM2, all the wells are simulated as multi-node wells using the MNW2 package [55], which allows for a more realistic representation of wells with long screens that intersect multiple layers in the model.

In CVHM2, the total number of observation wells for heads and drawdowns and their spatial distribution greatly increased. Head and drawdown data were input into CVHM2 using the HOBs (locations and groundwater level) and the Hydmod (locations) packages [46].

CVHM2 was updated to include groundwater inflows along model boundaries from 56 small watersheds that were not simulated in CVHM1. The flows generated by these 56 watersheds were estimated using the Basin Characterization Model v8 (BCM) [56]. The BCM generates two flow values for small watersheds, which are referred to as recharge and runoff. The recharge values represent direct underflow from the watershed into the groundwater system [47]. The runoff values represent surface runoff from the watershed into ephemeral or intermittent streams [47].

In CVHM2, the well package is used to inject the recharged water into the groundwater system. Unlike most model input files, which have their units converted to cubic meters per day, the time series data for the small watershed flows was left in the units that BCM uses (acre-feet per month, ac-ft/month). A MODFLOW scale factor of 40.6 was used to convert from ac-ft/month to cubic meters per day (m^3/d). This scale factor was further adjusted during calibration for each small watershed to account for uncertainty in BCM estimates, resulting in an overall reduction in small watershed flows by about 20 percent compared to BCM estimates. The reduced small watershed contribution to groundwater can be explained because only portion of runoff and recharge is thought to enter the groundwater system. Recharge can flow laterally and contribute to groundwater discharge, including evapotranspiration (ET). Similarly, not all runoff infiltrates into the groundwater system and either remains as surface flow or is lost to ET.

Farm Process (FMP)

In CVHM2, the Farm Process (FMP) is used to represent irrigated agriculture and water use. An overview of the FMP in the first 20 pages and Appendix 3 of [53], and input is described in Appendix 6 of [53]. Features added after 2020 and input changes are documented in the CHANGELOG.md and FMP_Template.fmp files in [52]. The FMP represents water use for each WBS, which are areas that rely on a common source of water and that have runoff returning to the stream network at the same locations.

The FMP uses an accounting area, referred to here as a WBS to calculate the supply and the demand over a group of model cells. The demands include potential evapotranspiration (PET) and urban usage, while the supplies include surface-water deliveries, precipitation, and MAR. In CVHM2, the FMP consumptive use (CU) is computed from reference evapotranspiration (ET_{ref}) and a crop coefficient (Kc; [113]). The "water demand" is then satisfied from (in order of priority) precipitation, imported water, surface water, and groundwater. Imported water, called a non-routed delivery (NRD), represents any supply that is not directly simulated by the model but is available for a WBS. An NRD can represent a water transfer or surface-water diversion from outside the model domain, a water pipeline that imports water, or any water delivery or movement that is not represented by surface-water features in the model. Surface water is provided to meet water demand via a diversion from the Stream Flow Routing Package (SFR) [114,115] called a semi-routed delivery (SRD) [52,53]. Multiple SRDs can serve a single WBS, and the water provided can be limited via administrative constraints or available flow in SFR. Groundwater supply is provided by the well construction defined in the Multi-Node Well Package (MNW2) [55], and the extraction (or injection) rates are set by FMP. The groundwater pumping is determined by the remaining demand after the available water supply from precipitation, NRD, and SRD are fully consumed. In a sense, this means FMP assumes well-watered/ideal conditions are met. Changes from the ideal conditions would need to be accounted for in other ways, such as with Kc, scale factor, or deficit irrigation.

In the FMP, irrigation and precipitation that are not consumed either become surface runoff or infiltrate to groundwater (deep percolation). In CVHM2, efficiencies are specified by land-use type, year, and WBS. These can be used to account for excess irrigation based on irrigation method or for salinity flushing. Currently, soil moisture is not accounted for in the FMP. Surface runoff within a WBS flows to a user-specified SFR locations called semi-routed return (SRR) points. FMP can automatically determine SRR locations, but FMP was not used to automatically determine SRR locations in CVHM2 because SRR locations are known for each WBS. Surface runoff can also flow out of the model to represent a stream that is beyond the model domain. Deep percolation represents vertical flow out of the soil and root zone that is simulated by FMP. A portion of the deep percolation can become surface runoff (rejected infiltration) if the rate exceeds the soils surface vertical hydraulic conductivity.

The FMP defines bare soil as any area in a WBS that is not defined by a land use. In CVHM2, each surface model cell includes one land-use type that occupies a portion of the model cell. Because much of the Central Valley is relatively arid, the rest of the area within cells cell was treated as bare soil. Bare soil does not have transpiration, and CVHM2 computes precipitation and groundwater evaporation for bare soil based on a bare soil crop coefficient and ET_{ref}. This method results in recharge being equal to monthly precipitation minus monthly bare soil evaporation. Precipitation that does not evaporate becomes runoff or deep percolation based on a bare soil runoff coefficient.

Soil Properties and Land Use

The FMP defines soil properties that are used for adjusting the PET associated with a land use, for calculating groundwater evapotranspiration and effective precipitation, and for determining when groundwater recharge is rejected (because the recharge rate is greater than the soils maximum infiltration rate). In CVHM2, runoff coefficients are defined by land-use type for all parts of the model. The FMP soil input for CVHM2 specifies a capillary fringe length for groundwater evapotranspiration and surface vertical hydraulic conductivity for rejected infiltration. These values mimic those specified by [41]. The FMP land use input defines crop coefficients and irrigation methods, root depths and suction pressures, from precipitation and irrigation. The FMP land use properties are documented in [29].

Climate

The climate input for CVHM2 specified the monthly precipitation rate and monthly reference evapotranspiration rate (ET_{ref}). The precipitation and ET_{ref} are derived from the Basin Characterization Model v8 (BCM) [56] on a 270-m grid and resampled to the 1.6-km by 1.6-km model grid in CVHM2; these values are documented in the CVHM2 Climate Data release [47]. [5] explains the details on how climate is used by the FMP. Generally, groundwater models derive ET and recharge outside of the model as a preprocessing step. The FMP uses precipitation data directly for accounting of runoff, recharge, and ET; however, partitioning of precipitation into runoff, recharge, and ET is strongly affected by rain intensity and may be lost during monthly averaging.

Direct Recharge

Managed aquifer recharge (MAR) from water banking, urban recharge, and canal seepage were simulated using the direct recharge option in the FMP. MAR data are documented by [44]. Recharged water was simulated by evenly dividing it to all the cells in each WBS associated with each water bank. Scale factors were estimated during calibration to adjust the amount of water recharged to account for unknown variations from the amount of recharge reported and the amount reaching the groundwater table. These differences could be due to non-recoverable losses, such as evaporation, or due to inaccurately documenting recharge.

In CVHM2, urban outdoor water use is simulated as a non-irrigated crop type, and its demand is met with precipitation and by root uptake. MNW2 pumping for urban and urban diversions are not sent back to the FMP. To account for the percolation of excess landscape irrigation, which is typical in many lawns in urban landscaped areas in the Central Valley, the direct recharge option in the FMP was used. Basically, outdoor domestic water use was represented in the model by removing domestic pumping from the model and applying outdoor domestic irrigation return flows as recharge using the FMP direct recharge option. However, outdoor domestic irrigation was not explicitly simulated. A coefficient of 79,000 cubic meters of water per cell per year is recharged for each urban land use cell. This value was fixed because it could not be estimated uniquely with the available observation data during calibration.

The SFR network only includes major streams and canals in the Central Valley. Data were not available to simulate all the local canals and channels that connect the SFR network to the place where diversions are used, and this type of complexity is not consistent with the rest of the model representation. The seepage from canals not represented in the model was simulated using the direct recharge option in the FMP. One value was used to represent direct recharge from canals delivering to each WBS, and this value for each WBS was estimated during the calibration process.

Surface-Water Deliveries (Diversions)

Surface-water deliveries in CVHM2 represent surface water used to meet water demands calculated by the FMP. The two types of surface-water deliveries simulated in CVHM2 are semi-routed deliveries (SRD) and non-routed deliveries (NRD). SRDs represent a diversion along the SFR stream network that removes water for beneficial use, such as irrigation or MAR [53]. In addition to agricultural diversions, exports from the streamflow network to areas outside of the Central Valley are simulated by delivering water to a virtual WBS (WBS 136) that is used for tracking diversions that route water outside the model. Urban diversions from the streamflow network are also simulated using WBS 136. NRDs represent diversions into the model from outside of the model area. In some areas NRDs were used to indirectly simulate diversions from within the model area.

CVHM1 simulated 66 SRDs from modeled streams. The diversion data in CVHM2 were updated to include 537 SRDs and 7 categories of NRDs. Compared to the CVHM1, the number of diversions in the CVHM2 greatly increased in the Delta and the western San Joaquin Valley. A major update in CVHM2 is that SRD diversions are simulated by the FMP rather than SFR. Previously, CVHM1 virtual diversion segments (sometimes referred to as "dummy segments") were used to connect SFR and the FMP. Based on the demand calculated for each WBS, FMP would remove the amount of water from the dummy segment necessary to meet the demand until all the water was diverted (supply limited from stream). All dummy segments were removed for CVHM2, and multiple SRD points at their actual diversion locations were used to connect SFR and FMP.

CVHM2 diversions are documented in [44], which includes a section that describes the data processing steps used to develop FMP input files from the available data.

Runoff

Surface drains remove water from groundwater when the head exceeds a user specified drain elevation. The water is removed at a rate based on the conductance of the drain and the water table elevation relative to the drain elevation. Drains in CVHM2 are simulated using the Drain Return Package (DRT) and linked to the FMP and SFR packages [52,53]. Each DRT drain is associated with an FMP WBS that collects the drain flow as runoff. The DRT-derived runoff is applied to SFR based on the FMP semi-routed return locations. The DRT-FMP-SFR linkage input is documented in the Model Setup Files data release [45].

Subsidence

The Subsidence and Aquifer-System Compaction (SUB) package [51–53] was used for simulating land subsidence in CVHM2. This package simulates compaction of the aquifer system due to the drainage of groundwater from compressible aquifer-system materials. The SUB package simulates instantaneous (referred to in [51] as "no-delay") and delayed drainage and compaction. The SUB package also simulates elastic and inelastic compaction. The SUB package was further enhanced in MODFLOW-OWHM to allow the use of parameters (along with arrays from the MULT and ZONE packages [50,52,53]) to define input datasets. The SUB package was modified to output various components of the subsidence simulation. These new output files include the separations of delay and instantaneous compaction and flows, separations of elastic and inelastic compaction and flows, delay interbed heads, and initial critical heads.

Simulation of subsidence in CVHM2 is divided into three major parts:

- Delayed compaction in the aquifer system above and below the Corcoran clay,
- Instantaneous compaction in the aquifer system above and below the Corcoran Clay, and
- Compaction in the Corcoran Clay.

Because the specific-storage properties of the aquifer-system material are represented in the subsidence package, the specific storage calculated in the MULT package [50,52,53] and used the Upstream Weighting (UPW) package [52,53] only accounts for the compressibility of water in the pore spaces of the aquifer. This method avoids "double counting" the specific storage of the aquifer-system material when the SUB package is used.

Delay vs Instantaneous

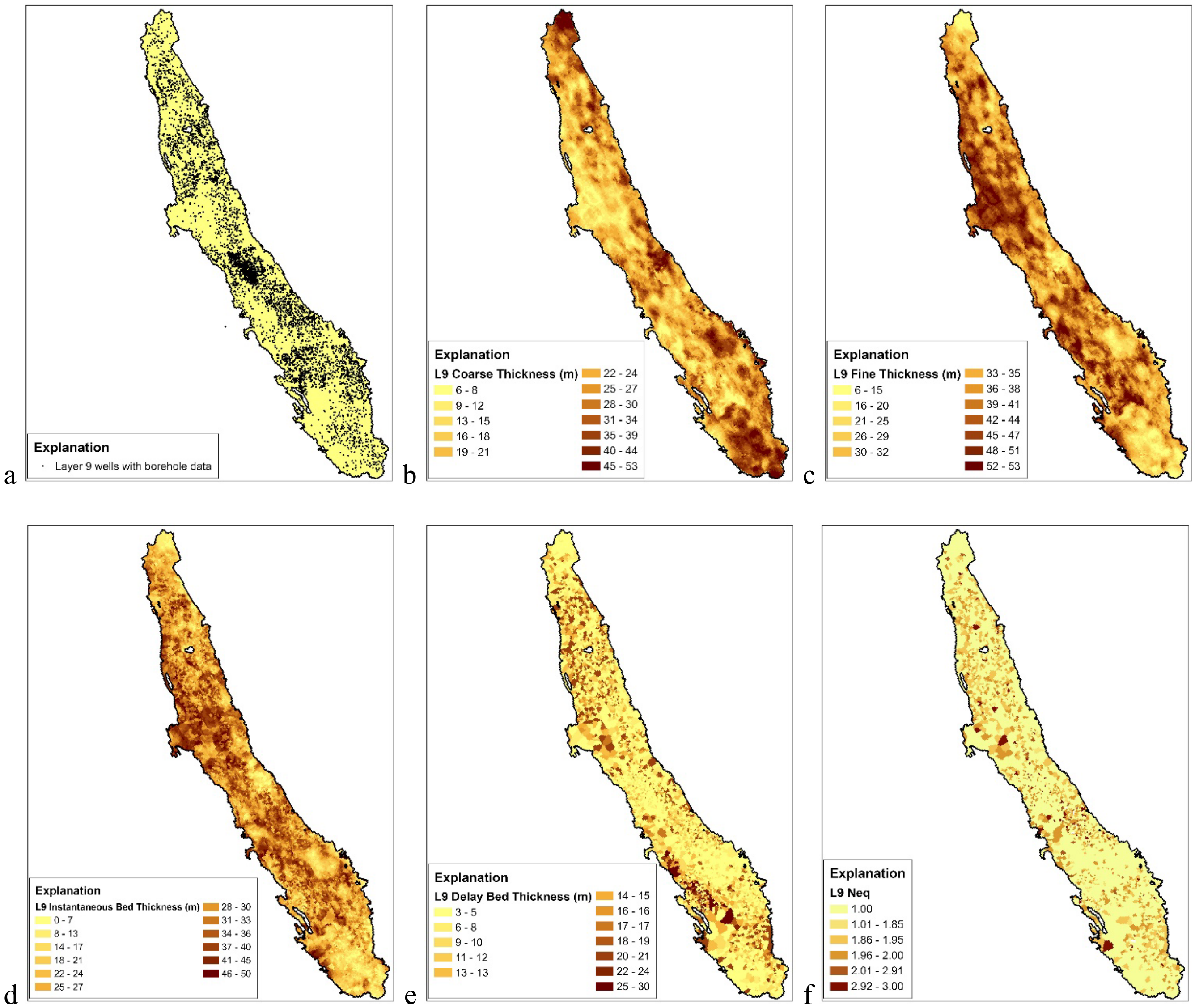
One of the major updates in CVHM2 is the addition of simulation of delayed compaction. In CVHM1, only instantaneous compaction was simulated, so if the groundwater head in a model cell dropped below the critical head, inelastic compaction would occur immediately. The Subsidence and Aquifer-System Compaction (SUB) package [51–53] was used to simulate the magnitude and extent of both delay and instantaneous aquifer-system compaction that results in land subsidence. Interbeds with a thickness of greater than 3 meters within a model layer are simulated using the delayed compaction option, and all thinner interbeds within a model layer are simulated using instantaneous compaction. Drillers' logs were used to estimate the number of delay interbeds and the equivalent thickness for the delay interbeds [33].

Delay Interbeds

To determine the thickness of the delay interbeds within each model cell (for layers other than the Corcoran Clay), the well-logs database [33] was used. The Beq and Neq arrays for each model layer are documented in CVHM2: Subsidence Package data release [46].

As an example, layer 9 thickness is explored to better understand the different thickness arrays that are calculated in CVHM2. Location of wells perforated in layer 9, total layer thickness, total thickness of coarse-grain deposits, total thickness of fine-grained deposits, total thickness of delay interbeds, total thickness of instantaneous interbeds, number of equivalent interbeds (Neq), and equivalent thickness of interbeds (Beq) are shown in figure S8. A total of 5,338 wells (out of the total 14,683 wells) in the well logs database [33] were perforated in Layer 9 (fig. S8a). Layer 9 thickness is a constant 59.0 meters, and the thicknesses of fine and coarse materials range from 5.9 (10 percent fine or coarse) to 53.0 m (90 percent fine or coarse) (fig. S8b and fig. S8c). The thickness of the instantaneous beds ranges from 0 (not present) to 50 m (fig. S8d). The delayed thicknesses range from the imposed minimum value of 3 meters to a maximum of 29.8 meters (fig. S8e). The texture model percentage of coarse-grained materials was calculated at 15-m depth increments; however, the original lithologic data were reanalyzed at 1-m thick intervals to determine the thicknesses of individual interbeds within a cell for the purposed of the Neq and Beq calculation. For layer 9, 5,338 wells with borehole data were used for the Beq and Neq calculations. Cells without borehole data used borehole data from the closest cell using Thiessen Polygons [116]. The Neq for layer 9 ranges from 1 to 4 interbeds per model cell (fig.

S8f), and the Beq of each interbed ranges from 3 to 25 meters (fig. S8g). A check was performed to compare the total thickness of delay bed (Beq times Neq) for all cells to the total thickness of fine-grained materials (calculated as percentage fine-grained times layer thickness). If needed, Beq was reduced to not exceed total thickness of fine-grained materials.



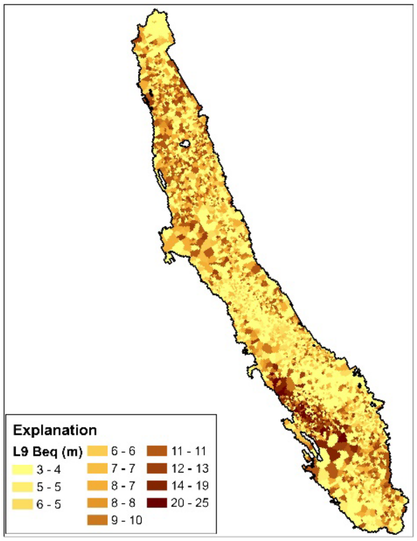
g 

Figure S8. (a) Location of wells, (b) total thickness of coarse grain deposits, (c) total thickness of fine-grained deposits, (d) total thickness of instantaneous interbeds, (e) total thickness of delay interbeds, (f) number of equivalent interbeds, and (g) equivalent thickness of interbeds for Layer 9 in CVHM2.

In addition, for the equivalent number of delay interbeds and equivalent thickness of the delay interbeds, the following datasets were defined in the SUB package for simulation of delayed compaction: starting delay bed critical head, starting delay bed head, elastic specific storage, inelastic specific storage, and vertical hydraulic conductivity. Critical head arrays were updated as needed during model calibration if the model was experiencing unexpected high magnitudes of compaction (or expansion) during the first few stress periods of the simulation. Starting delay bed heads were set to the same value as the critical head. Initial parameter values for elastic specific storage, inelastic specific storage, and vertical hydraulic conductivity were derived from previous studies [5] (Table S2). These values were defined and adjusted during model calibration using 17 total parameter zones [48]. Parameters zones 1-8 are used for aquifer layers 1-5 (above Corcoran Clay), parameters zones 9-16 are used for aquifer layers 9-13 (below Corcoran Clay), and the Corcoran Clay parameter values were assigned separately. The same horizontal grouping was used for the above and below Corcoran Clay zones; in other words, zones 1 and 9, 2 and 10, 3 and 11, etc. correspond horizontally to the same cells. Scale factors for shifting starting critical head shifts were also defined by the 17 parameter zones.

Table S2. Initial parameter values for elastic specific storage (sske), inelastic specific storage (sskv), and vertical hydraulic conductivity (Kv). (a) from 1-D subsidence simulation [117]. (b) from other previous studies

(A)	Sske (m^{-1})	Sskv (m^{-1})	Kv (m/d)
[48,117] above Corcoran Clay	5.2E-07	1.8E-04	6.4E-06
[48,117] Corcoran Clay	5.2E-07	5.5E-04	5.5E-07
[48,117] below Corcoran Clay	5.2E-07	2.0E-04	5.2E-06

(B) source	min Sske (m^{-1}), fine	max Sske (m^{-1}), fine	min Sskv (m^{-1}), fine	max Sskv (m^{-1}), fine	min Sske (m^{-1}), coarse	max Sske (m^{-1}), coarse	Sske (m^{-1}), coarse + fine	min Kv (m/d), fine	max Kv (m/d), fine
[22,118–120] (CV)	6.1E-07	2.3E-06	4.3E-05	2.0E-04	2.8E-07	4.3E-07	9.1E-07	--	--
[5] (CV)	1.4E-06		4.3E-05		3.0E-07		--	--	--
[79,84,118–121]	--	--	--	--	--	--	--	1.0E-07	2.8E-06

Instantaneous beds

The thickness of the model layers that was not simulated using delayed compaction was simulated using instantaneous compaction. This remaining thickness includes interbeds less than 3-meter thick and coarse-grained materials that are not inelastically compressible but are elastically compressible. For each model cell, the thickness of the coarse-grained materials was calculated by multiplying percent coarse from the aquifer texture model by the layer thickness. The thickness of instantaneous fine-grained materials was calculated by multiplying percentage fine-grained deposits by the layer thickness and then subtracting the thickness of fine-grained materials being simulated using delay. Similar to the delay beds, initial values for the critical head were initially set to the starting groundwater head in the model. These values were updated as needed during model construction and calibration to avoid unrealistically high compaction (or expansion) during the first few stress periods of the simulation.

Corcoran Clay

Previous studies indicate that the Corcoran Clay is compacting very slowly [5]; therefore, we simulated Corcoran Clay using dedicated model layers (model layers 6, 7, and 8), with significantly lower vertical hydraulic conductivities than the surrounding model layers. The lower vertical hydraulic conductivities cause delays for the head to equalize with the lower heads in the surrounding aquifer. As such, the model represents delayed compaction in the Corcoran Clay without using the delay option.

Streamflow

The conveyance of surface water in the Central Valley and the interaction between surface water and groundwater is simulated by the streamflow routing package (SFR) [52,53,115]. For CVHM2, the representation of the surface-water network was expanded and enhanced to allow transmission and interaction between groundwater and surface water. Specifically, the network was updated to include: 1) additional features in the streamflow network, 2) streambed elevations, 3) inflow data, 4) separation of time series for inflows and bifurcation flows, and 5) diversions in the FMP rather than the SFR (discussed in the FMP section) [44,45] (fig. S9).

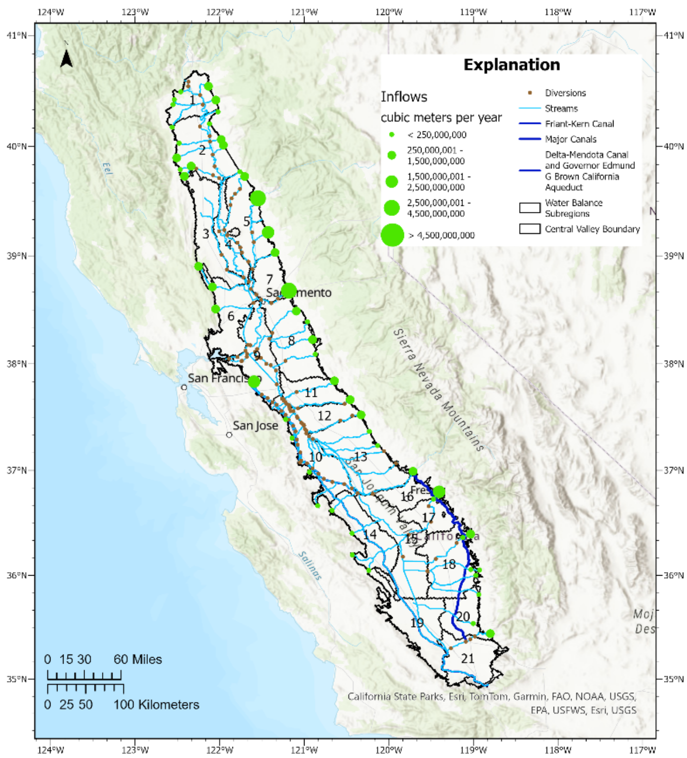


Figure S9. Streamflow network, locations of inflows, locations of diversions, and stream-flow routing (SFR) cells.

The surface-water network includes additional streams, canals, and bypasses: 1) 5 new streams were added in the Sacramento Valley, 2) 11 new streams were added in the San Joaquin Valley, 3) 13 major flood control bypasses were added, and 4) the California Aqueduct and the Delta-Mendota Canal were added.

Bifurcation rules were updated to better simulate the Kings River flood flows that go up the Fresno Slough and James Bypass into Mendota Pool. In the Tulare Basin, the stream segments end points were connected to represent flow to Tulare Lake. Although CVHM2 simulates additional streams, canals, and bypasses, the SFR input file and overall SFR network are simplified in CVHM2 compared to CVHM1.

(S3) Model Calibration

The calibration of CVHM2 was accomplished using a similar method as CVHM1, using a combination of trial-and-error and semi-automated methods [5]. Like CVHM1, observation data were compared to their simulated equivalent to provide a measure of the model's performance. CVHM2 used the public-domain model-independent parameter-estimation program, PEST_HP version 17.4 [122] for the automation.

Observations

CVHM2 builds on CVHM1 observation datasets representing: 1) groundwater levels and change in groundwater levels (drawdowns and trends), 2) subsidence and compaction, 3) streamflow, and 4) drain flow observations [46]. In addition, the groundwater level and change in groundwater levels (drawdowns and trends) datasets used in CDWR's C2VSim model [41,42] were added to CVHM2. Overall, 362,254 observations (and 13 predictions) were included in the calibration process.

In some locations, the density of available observations was greater than one site every 1.6 kms. Because the plan-view area of cells in CVHM2 are 1.6-km by 1.6-km, if two observations sites of the same type were in the same cell, the observation site with less representative data may have been removed to prevent conflicting observation data. For example, if two benchmark sites from the same survey are in the same cell, only one site would be selected. However, two benchmark sites from the different surveys would both be used because they are measuring data from different periods. Compaction, subsidence, and streamflow measurements are often measured more frequently than the monthly stress periods in CVHM2. For compaction and subsidence observations, temporally dense records were averaged to one value per month as previously shown (fig. S4) [46]. For streamflow observations, monthly average streamflow values were calculated from daily observations [46]. Compaction and subsidence were assumed to be zero during periods for which data were missing.

However, to exclude data gaps longer than 4 years from model observations, sites with these gaps were split into separate “virtual sites” when imported into the model. For example, site 12S12E16H002 (shown in figure 3e of the main article), was split into two “virtual sites” to account for the data gap from 2000 to 2008. Separating the sites in this manner allows the model to simulate compaction and subsidence during the data gaps without creating “penalty” on the calibration objective function.

Weights were assigned for each observation. The first purpose of observation weights was to account for differences in measurement types. Weights were assigned to each observation type according to the magnitude of the values so that the contributions to the objective function were roughly equal for different types of observations. The second purpose of weights is to give a higher relative weighting to selected observations where it was determined that matching those specific observations was important conceptually to the overall calibration of the model. For example, of the 922 subsidence observations sites, a set of 37 “subsidence key observation” sites were created that represented overall subsidence patterns in the Central Valley and simplified assessment of model performance during calibration. These sites are referred to as the “keysub” group in the PEST control file and are given a higher weight compared to other subsidence observations. The keysubs included sites spread between the 21 WBSs to ensure a spatial distribution of sites. The type of subsidence observation site was considered when choosing the keysubs. Data from extensometers and benchmark sites typically have observations covering longer time periods than InSAR data, which are only available starting in 2003. Extensometers also measure compaction in specific vertical intervals in the aquifer system rather than for the entire aquifer system. Thus, extensometers provide calibration data for specific model layers, such as only the layers above the Corcoran Clay, which can improve the simulation of compaction both above and below the Corcoran Clay.

Parameters

Parameters represent important hydrologic properties input to the model that are adjusted during calibration to improve the model's fit to observation data. The details of these parameters are described in [5]. For reference, some of the parameter information is repeated here, but the reader is referred to the documentation on CVHM1 for more details. Parameters were grouped into similar types based on function and purpose for the calibration [59]. In all, 780 parameters, categorized into 13 parameter groups, were included in the calibration process. Building on methodology of CVHM1, CVHM2 uses the texture-based approach for hydraulic properties. A global hydraulic conductivity was calibrated for coarse material and fine material for the Sacramento Valley and San Joaquin Valley, and initial values were calculated based on the percent coarse value for each cell using a power mean [5]. The coefficient of the power mean was estimated for the Sacramento and San Joaquin Valleys.

Separate hydraulic conductivity values were estimated for the various geologic formations at the margins of the Central Valley and the Corcoran Clay. To account for local variability, CVHM2 includes a chain of unitless scale factors to delineate spatial variations in hydraulic conductivity. Depth decay factors were also estimated to account for the fact that deeper aquifer-system material is generally more compacted and will have a lower hydraulic conductivity compared to the same material in the upper aquifer system. Like CVHM1, a variety of storage properties were estimated [5]. For the compaction related parameters, fine elastic specific storage, coarse elastic specific storage, and fine inelastic specific storage were defined using parameters for both delay and instantaneous beds [48]. For delay beds, vertical hydraulic conductivity was estimated. For the calibration process, different groupings were developed to reduce the total number of compaction parameters needed to be estimated. Other parameter values were fixed, were not estimated, and were based on well-defined values from previous studies; other parameters were fixed because they were not sensitive in the calibration process.

Starting head values in each cell were either adjusted upward or downward based on the values calculated using the parametric grid of pilot points. Several recharge parameters were estimated in the model. One value for direct recharge due to canal seepage for each WBS as well as one value for direct recharge from the canals off the Delta-Mendota Canal were estimated. Another set of scale factors was estimated for each of the recharge fractions from water banks. For the small watershed recharge, scale factors were adjusted for the recharge and runoff values of each watershed to account for uncertainty in BCM estimates. Also, the scale factor was reduced for the runoff values because not all the runoff flow contributes to recharge; some of the flow either evapotranspires or flows out of the model as surface flow.

Several parameters were used in FMP [59]. Parameters were used to define the "baseline" irrigation efficiencies for the 24 land-use types. CVHM2 also includes a chain of unitless scale factors to control temporal and spatial variations in irrigation efficiencies. These scale factors include a global by-decade adjustment. Scale factors were estimated to better capture seasonal variations (growing season vs non-growing season) and water year variations (dry, normal, and wet) in the crop coefficients. Soil properties, including capillary fringe depth, were calibrated for each of the soil categories simulated in the model [5]. Maximum precipitation was estimated and set a limit on how much precipitation could contribute to water use (either by native vegetation, agricultural, or urban land uses). Precipitation in excess of the estimated maximum precipitation for a given soil group becomes runoff. Bare soil runoff factors, which control the ratio of runoff to recharge on bare soil due to precipitation, were also estimated. The runoff fractions, which control the ratio of runoff to recharge due to precipitation, were also estimated by groups of similar land-use type.

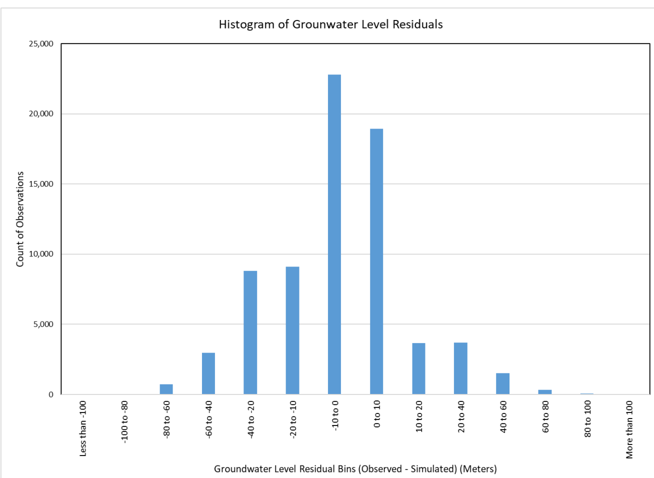
Calibration Process

The overall calibration process in CVHM2 is a nonlinear response between parameter change and observations, and parameter sensitivities varied greatly from one iteration to the next. CVHM2 includes a large amount of structural complexity and “noise”; therefore, manual calibration was necessary. Estimating compaction parameters using PEST is especially difficult. For example, when starting critical head values are below the groundwater head for the entire simulation, starting critical head values are insensitive. Over the range of values in which the critical heads are sensitive, estimates will change as the simulated groundwater levels change during calibration. In addition, elastic specific storage properties are generally not sensitive to subsidence observations because the elastic portion of simulated compaction is small compared to the inelastic portion. However, lowering the elastic specific storage will cause the simulated groundwater levels to fluctuate more, which can cause head to drop below the critical head and trigger inelastic subsidence. This effect means that elastic storage properties can be sensitive and that changes in elastic storage properties indirectly can make non-sensitive initial critical head value sensitive. Inelastic specific storage parameters are also relatively insensitive.

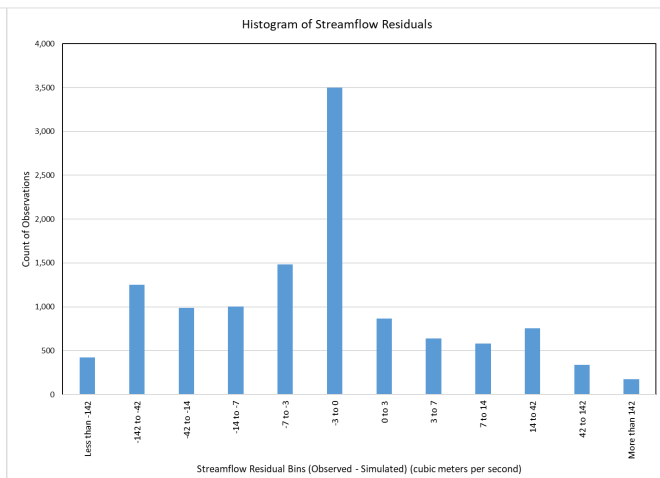
During the calibration process, the temporal and spatial components of groundwater budgets, water-use budgets, landscape budgets, and streamflow budgets were regularly analyzed. Hence, these budgets were treated as “soft” observation targets during the manual calibration process. Other “soft” calibration targets that were examined during calibration included the overall simulated groundwater level and subsidence maps, especially focusing on the locations and shapes of groundwater and/or subsidence depressions. PEST automation was used to assist in the manual calibration process, and as manual calibration was closer to a solution, the automated calibration process became more stable. However, in many cases, PEST was still unstable, and adjustments were made using trail-and-error (manual calibration).

Calibration Results

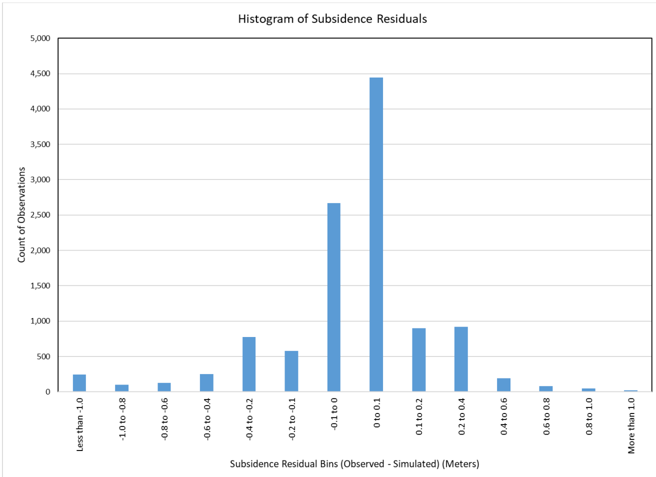
Calibration of CVHM2 proceeded such that the parameters remained in a reasonable range until a stopping point was reached [59]. Not all the parameters were estimated during calibration, but the parameters were retained in the model files. In this supplementary material, a residual is defined as observed minus simulated, which is the convention used in PEST. A histogram of residuals was examined to quantify the model fit between the simulated and observed values for groundwater level, streamflow, subsidence, and drain flow (fig. S10). During the calibration process, some observation groups were not as representative as other groups and were given lower weights. Also, some observations were outliers and were removed from the calibration by setting their weight to zero. These outliers were also removed from the plots.



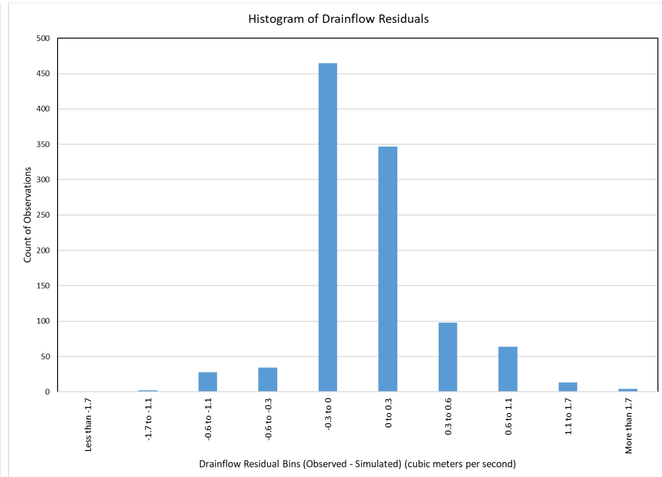
(a)



(b)


Histogram of Subsidence Residuals
Count of Observations
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
Less than -1.0
-1.0 to -0.8
-0.8 to -0.6
-0.6 to -0.4
-0.4 to -0.2
-0.2 to -0.1
-0.1 to 0
0 to 0.1
0.1 to 0.2
0.2 to 0.4
0.4 to 0.6
0.6 to 0.8
0.8 to 1.0
More than 1.0
Subsidence Residual Bins (Observed - Simulated) (Meters)

(c)


Histogram of Drainflow Residuals
Count of Observations
500
450
400
350
300
250
200
150
100
50
0
Less than -1.7
-1.7 to -1.1
-0.6 to -1.1
-0.6 to -0.3
-0.3 to 0
0 to 0.3
0.3 to 0.6
0.6 to 1.1
1.1 to 1.7
More than 1.7
Drainflow Residual Bins (Observed - Simulated) (cubic meters per second)

(d)

(e)

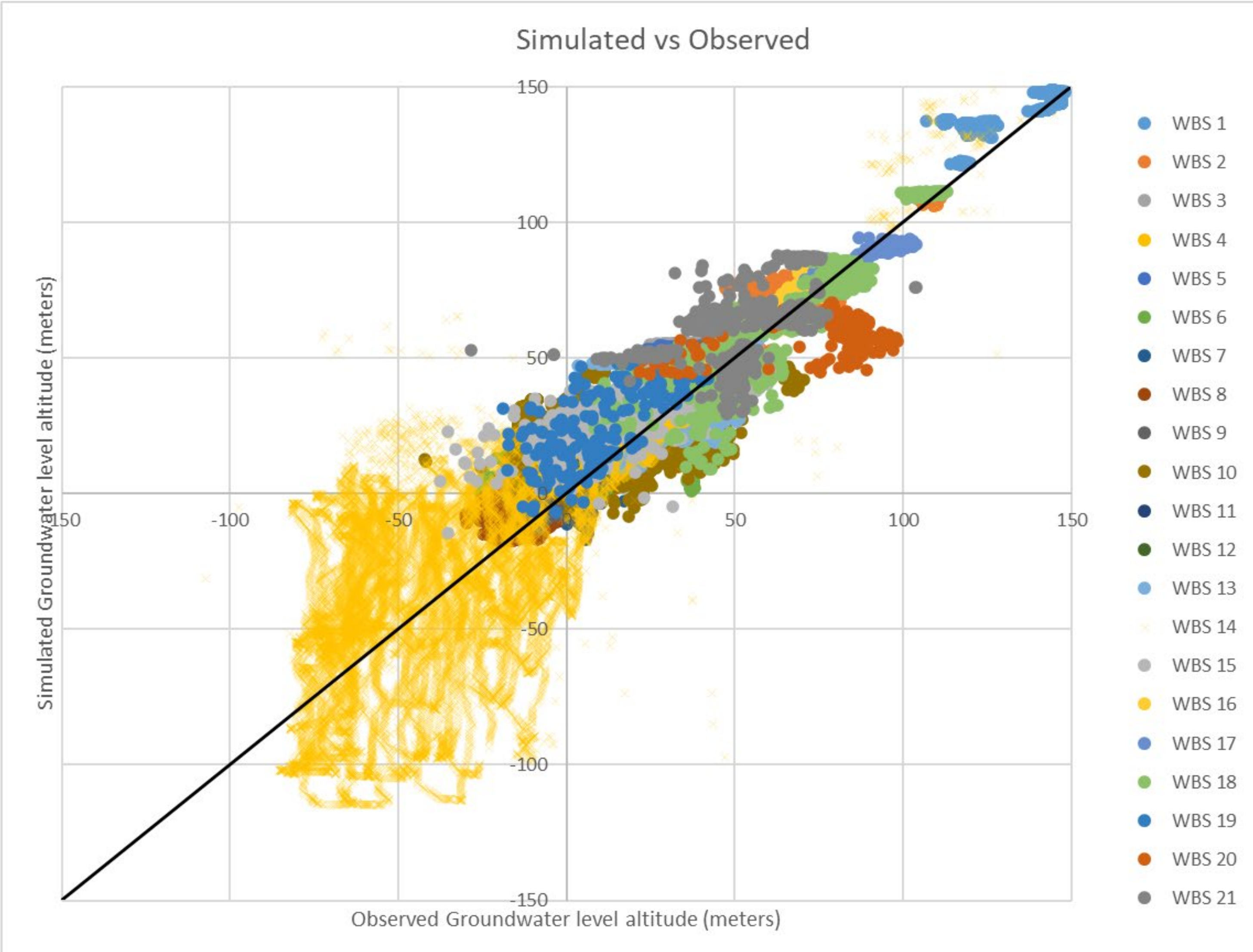


Figure S10. Histograms of monthly residuals for (a) groundwater level (b) streamflow, (c) subsidence, and (d) drain flow. (e) Observed vs Simulated Groundwater Level.

The average groundwater-level residual in CVHM2 for the “heads_gp” observation group is -4.6 meters (groundwater-level observations range more than 750 meters), which indicated that CVHM2 is slightly over simulating groundwater levels on the regional scaled 1.6-km by 1.6-km grid. Observation values often represent more local conditions. Even so, 57 percent of simulated groundwater levels are within 10 meters (m) of their equivalent observation, and 75 percent of the simulated groundwater levels are within 20 m of their equivalent observation. The simulated results demonstrate that matching simulated and observed subsidence values was a primary focus of the calibration effort. The average subsidence residual in CVHM2 is -0.023 m, and 63 percent of simulated subsidence values are within 0.1 m of their equivalent observation.

For groundwater level, observations are also plotted against their simulated equivalents (fig. S10e). Values that plot above the 1:1 line represent observations where the model is oversimulating groundwater (negative residual), and values that plot below the 1:1 line represent observations where the model is under simulating groundwater (positive residual). Generally, the data points fall near the 1:1 line without a noticeable bias toward oversimulating or undersimulating at any point along the line. The largest outliers are found in horizontal "clusters" of points, where the simulated values greatly exceed the observed values. These clusters represent single sites (observations taken from the same well at different times) where the CVHM2 is not accurate at local levels.

For monthly mean streamflow, 42 percent of simulated streamflows are within 2.8 cubic meters per second (m^3/s) of their equivalent observations, and 67 percent of the simulated streamflows are within 14 m^3/s of their equivalent observation. The average streamflow residual is in CVHM2 is -19 m^3/s, which indicates that CVHM2 is slightly overestimating streamflow. This overestimation is partially due to areas with shallow groundwater levels, especially in the Sacramento Valley. Because streamflow accumulates or is lost as it moves downstream, errors can accumulate or compensate and be present at downstream gages.

Drain-flow data were only available on the western side of the San Joaquin Valley; drain flows are important locally but represent a small component of the total groundwater budget (average annual drain flow is 0.3 percent of the average annual groundwater pumping). The level of calibration effort to match drain flows was small compared to matching other observation types, particularly subsidence.

The average drain-flow residual in CVHM2 is 0.79 m^3/s, indicating CVHM2 slightly undersimulates drain flows. The undersimulating may result from drains collecting irrigation water that is percolating down but that has not yet reached the groundwater system, which is not simulated in CVHM2; 77 percent of simulated drain flows are within 0.3 m^3/s of their equivalent observation, and 89 percent of the simulated drain-flow values are within 0.6 m^3/s of their equivalent observation. A full comparison of simulated vs observed values at all the sites calibrated in CVHM2 is provided in the CVHM2 data release [59]. Given the regional scale of CVHM2, these calibration results further demonstrate that CVHM2 simulated outputs reasonably match observations.

Parameter Sensitivity

The composite sensitivity of a model parameter is a measure of how much the simulated values (each corresponding to an observation) change with respect to a change in the parameter value. The parameter sensitivity and its importance are discussed in more detail in [5].

The composite sensitivity of a model parameter was estimated using the method by [122]. Multiplying the composite sensitivity by the parameter value results in the relative composite sensitivity, which allows for a better comparison of the composite sensitivities for parameters of different types and different magnitudes. Figure S11 shows the relative composite sensitivities of the 25 most sensitive parameters ranked in order from the most to the least sensitive. The top 25 most sensitive parameters comprise a mix of several different parameter types. The top three most sensitive parameters are all critical head shifts (critical heads are the heads below which inelastic compaction will occur) for upper aquifer-system layers in parameter zones within the Tulare Basin, which indicates that changing these parameter values will substantially change the simulated heads and amount of compaction in the upper aquifer-system layers. Several storage parameters, specifically several specific yield adjustments and several subsidence specific storage parameters, are the most sensitive parameters.

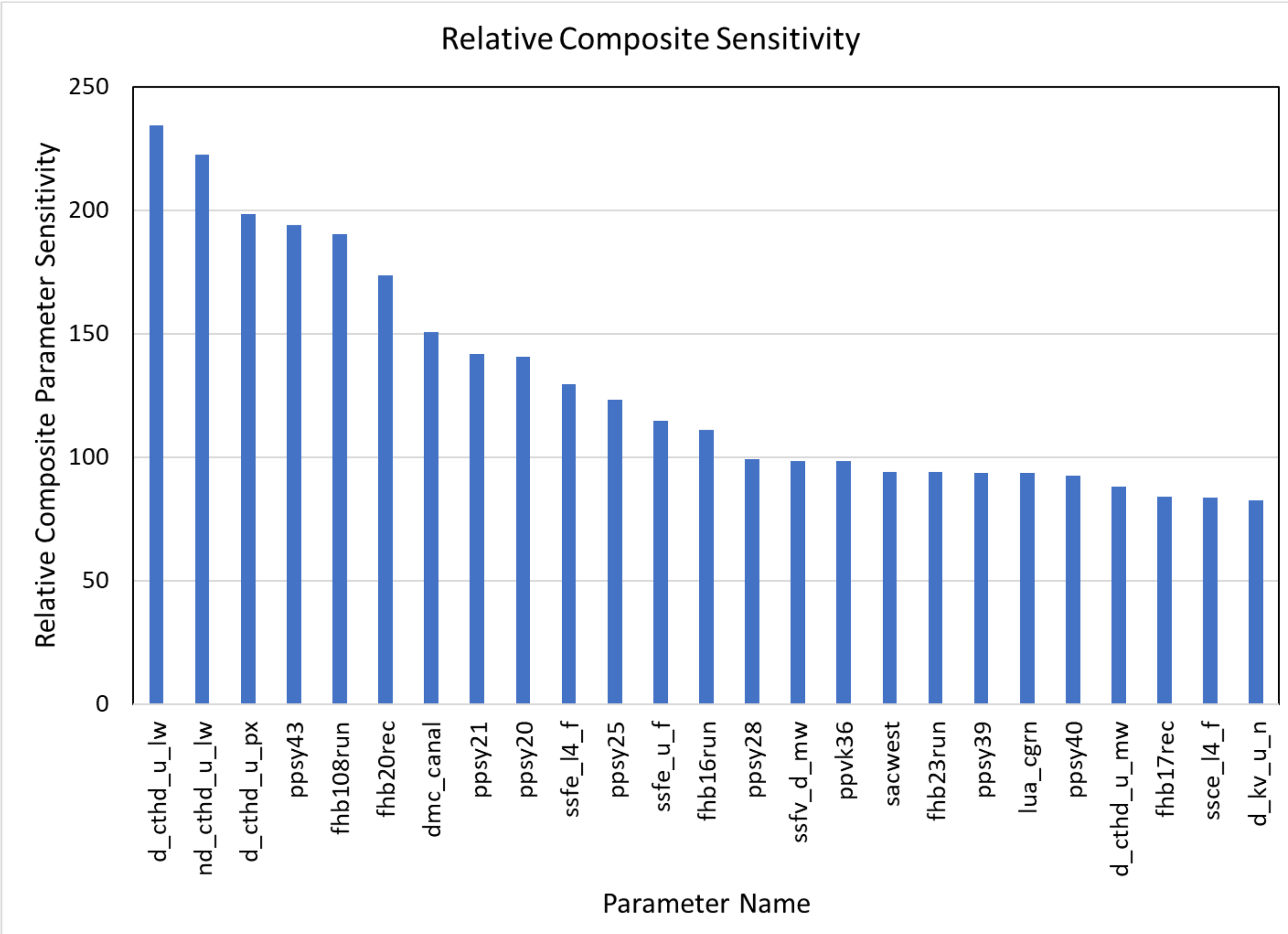


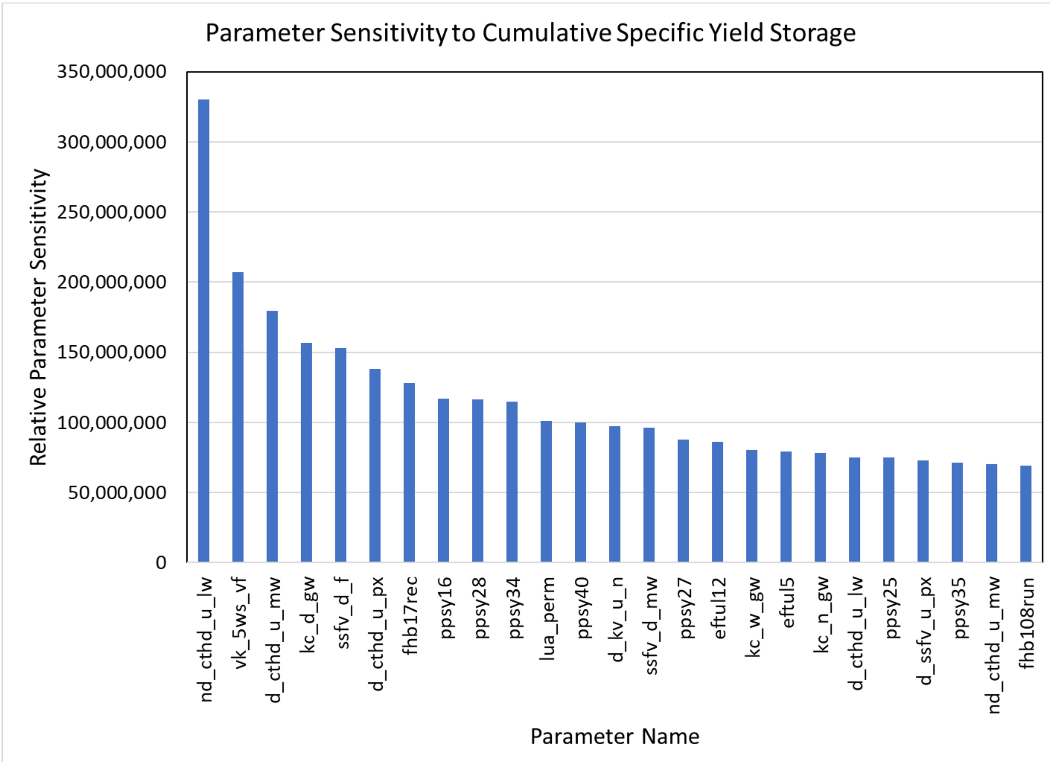
Figure S11. Relative composite sensitivities of the 25 most sensitive parameters of CVHM2. Parameter names and descriptions are found in table 7 of the CVHM2 model release [59].

Uncertainty Analysis

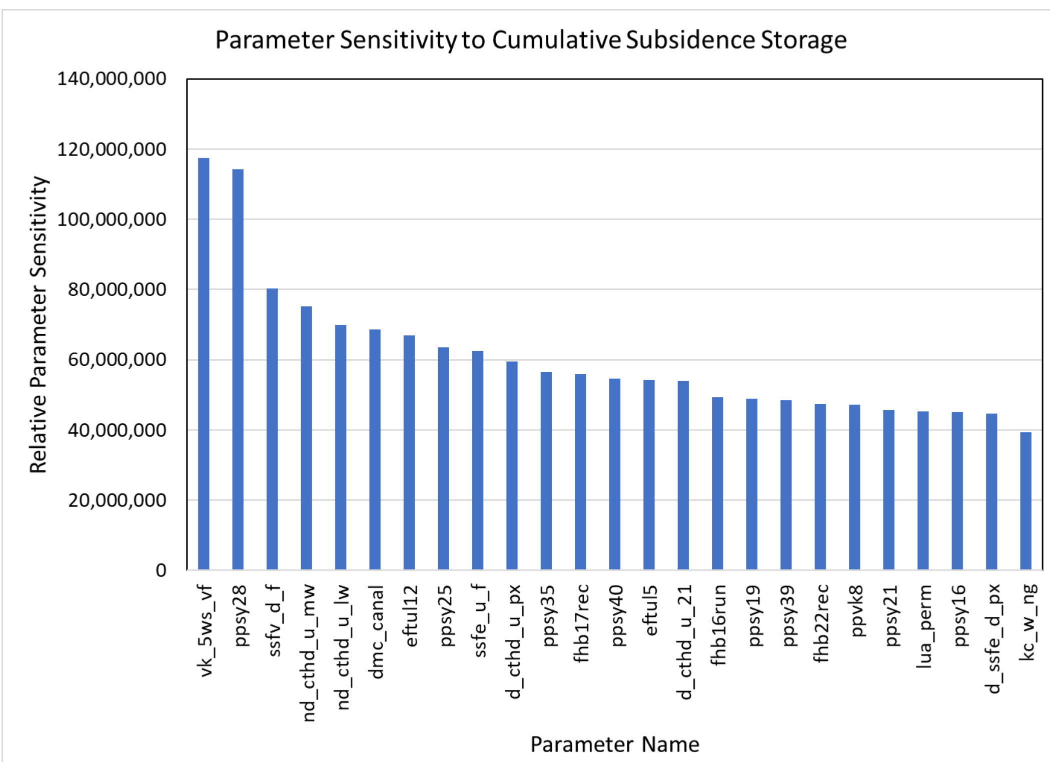
The sensitivity analysis measures the variability of the simulated values that correspond to observations around their calibrated values. PEST can also be applied to CVHM2 to determine which parameters contribute the most predictive uncertainty of key groundwater budget components. Figure S12 shows the parameters that contribute the most to the predictive uncertainty of: (a) change in storage from specific yield, (b) change in storage from compaction, (c) groundwater and surface-water interaction, (d) groundwater pumping, (e) groundwater recharge, and (f) small watershed recharge. A “sensitivity analysis” was performed for each of these budget components independently to determine the relative contribution of each parameter to the total prediction uncertainty. As would be expected, for simulated storage and simulated compaction storage, the most sensitive parameters are a mix of aquifer-system properties and FMP parameters (fig. S12a, fig. S12b).

Interestingly for groundwater and surface-water interaction, the most sensitive parameters are also a mix of aquifer-system properties and FMP parameters (fig. S12c). In fact, the most sensitive streambed conductivity parameter to stream seepage is ranked 41st on the list of most sensitive petameters (the “sactnor” parameter, which controls the streambed conductivities of the tributaries in northern Sacramento Valley). This result indicated that the overall groundwater and surface-water interaction is mostly influenced by: (1) the magnitude of the gradient between the stream stage and the underlying groundwater level, (2) Streamflow cells where the underlaying groundwater level is shallow, and (3) streamflow cells where the underlying aquifer conductivity is high. Streambed conductivities can also become insensitive above or below certain values, and the actual streambed conductivity could be much higher or lower than what is estimated.

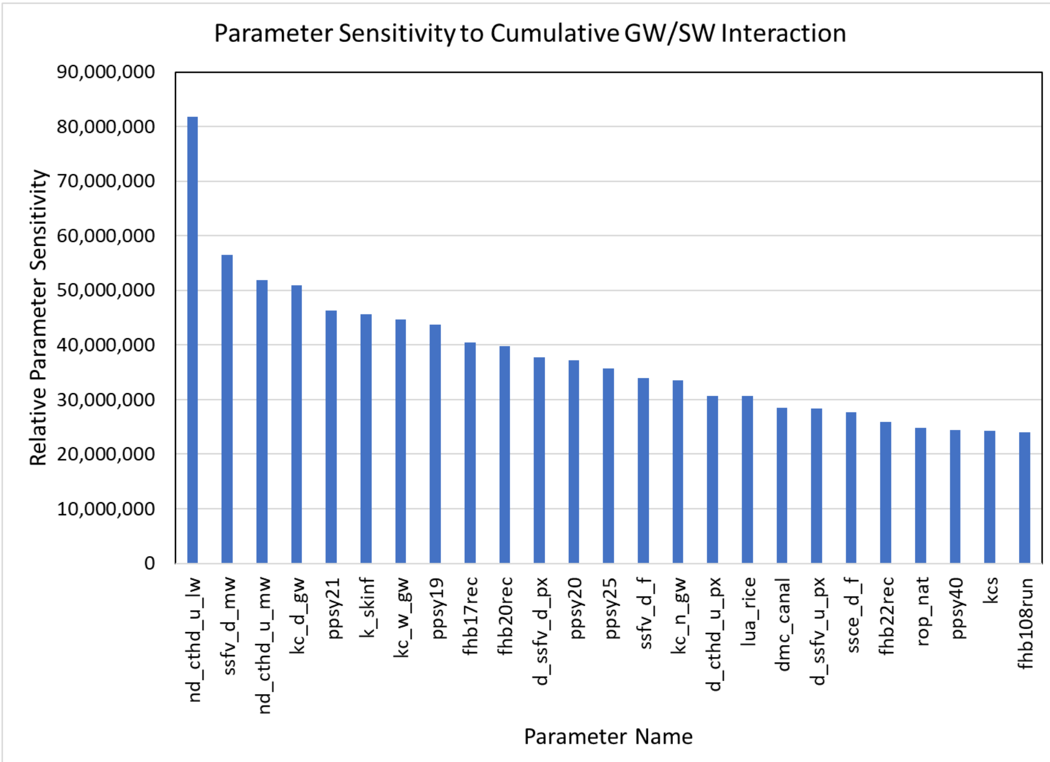
As expected, the simulated pumping is controlled by FMP parameters in the top 25 sensitive parameters, including crop coefficients, land-use area fractions, and irrigation efficiencies (fig. S12d). The conductivity of the well borehole skin for agricultural wells is also the 5th most sensitive parameter to simulated pumping, which indicates that some well pumping might be limited by the connection between the well and the aquifer. Likewise, the recharge was dominated by FMP parameters, mostly irrigation efficiencies (fig. S12e). Notably, only one runoff factor parameter, the runoff of precipitation for native classes, was ranked in the top 25 for recharge sensitivity. Unsurprisingly, the small watershed recharge is controlled by the small watershed recharge and runoff factors (fig. S12f).


Parameter Sensitivity to Cumulative Specific Yield Storage
350,000,000
300,000,000
250,000,000
200,000,000
150,000,000
100,000,000
50,000,000
0
Relative Parameter Sensitivity
nd_cthd_u_lw
vk_5ws_vf
d_cthd_u_mw
kc_d_gw
ssfv_d_f
d_cthd_u_px
fhb17rec
ppsy16
ppsy28
ppsy34
lua_perm
ppsy40
d_kv_u_n
ssfv_d_mw
ppsy27
eftul12
kc_w_gw
eftul5
kc_n_gw
d_cthd_u_lw
ppsy25
d_ssfv_u_px
ppsy35
nd_cthd_u_mw
fhb108run
Parameter Name

(a)


Parameter Sensitivity to Cumulative Subsidence Storage
140,000,000
120,000,000
100,000,000
80,000,000
60,000,000
40,000,000
20,000,000
0
Relative Parameter Sensitivity
vk_5ws_vf
ppsy28
ssfv_d_f
nd_cthd_u_mw
nd_cthd_u_lw
dmc_canal
eftul12
ppsy25
ssfe_u_f
d_cthd_u_px
ppsy35
fhb17rec
ppsy40
eftul5
d_cthd_u_21
fhb16run
ppsy19
ppsy39
fhb22rec
ppvk8
ppsy21
lua_perm
ppsy16
d_ssfe_d_px
kc_w_ng
Parameter Name

(b)


Parameter Sensitivity to Cumulative GW/SW Interaction
Relative Parameter Sensitivity
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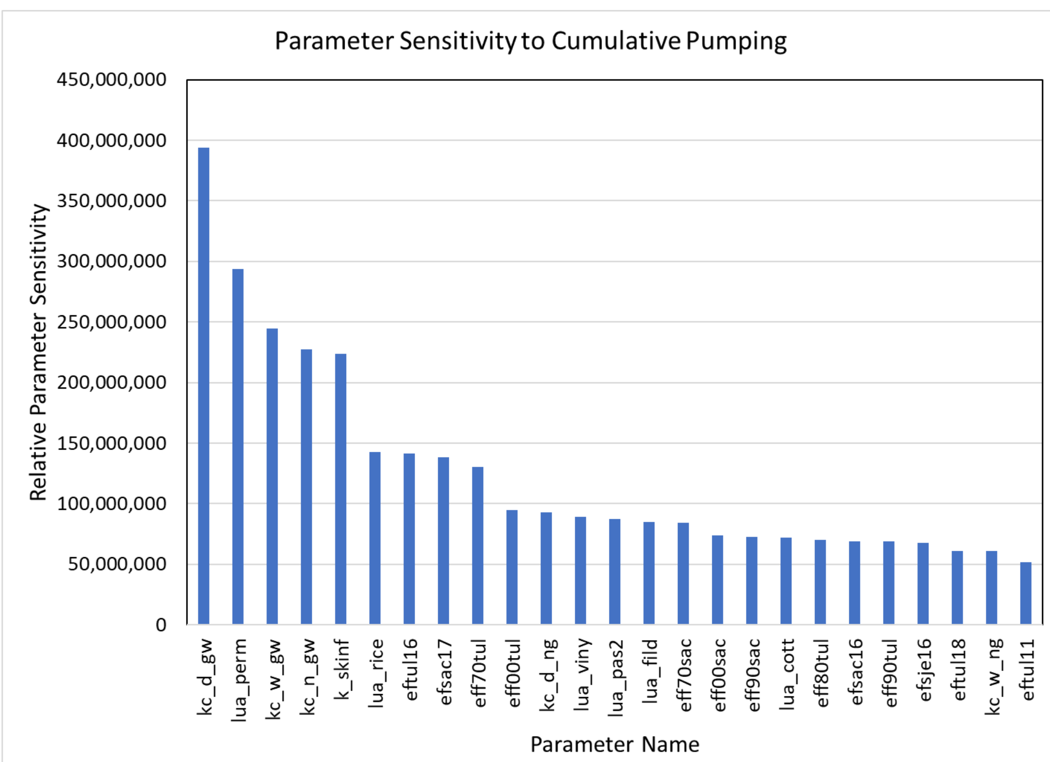
80,000,000
70,000,000
60,000,000
50,000,000
40,000,000
30,000,000
20,000,000
10,000,000
0
nd_cthd_u_lw
ssfv_d_mw
nd_cthd_u_mw
kc_d_gw
ppsy21
k_skinf
kc_w_gw
ppsy19
fhb17rec
fhb20rec
d_ssfv_d_px
ppsy20
ppsy25
ssfv_d_f
kc_n_gw
d_cthd_u_px
lua_rice
dmc_canal
d_ssfv_u_px
ssce_d_f
fhb22rec
rop_nat
ppsy40
kcs
fhb108run
Parameter Name

(c)


Parameter Sensitivity to Cumulative Pumping
Relative Parameter Sensitivity
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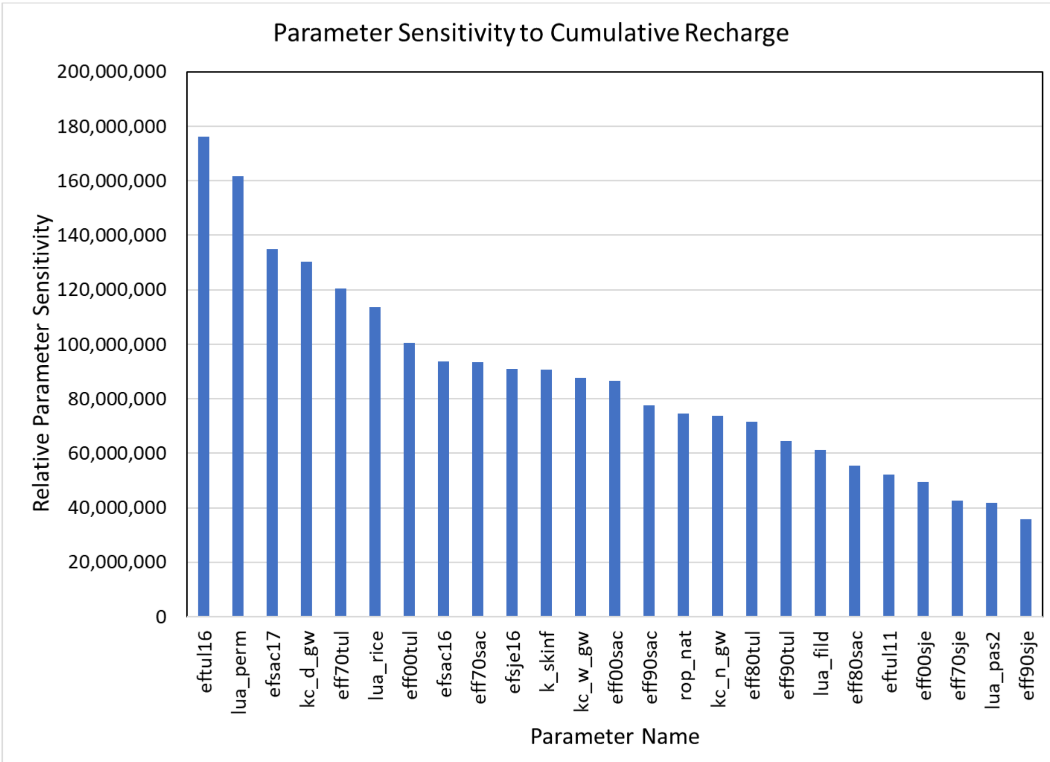
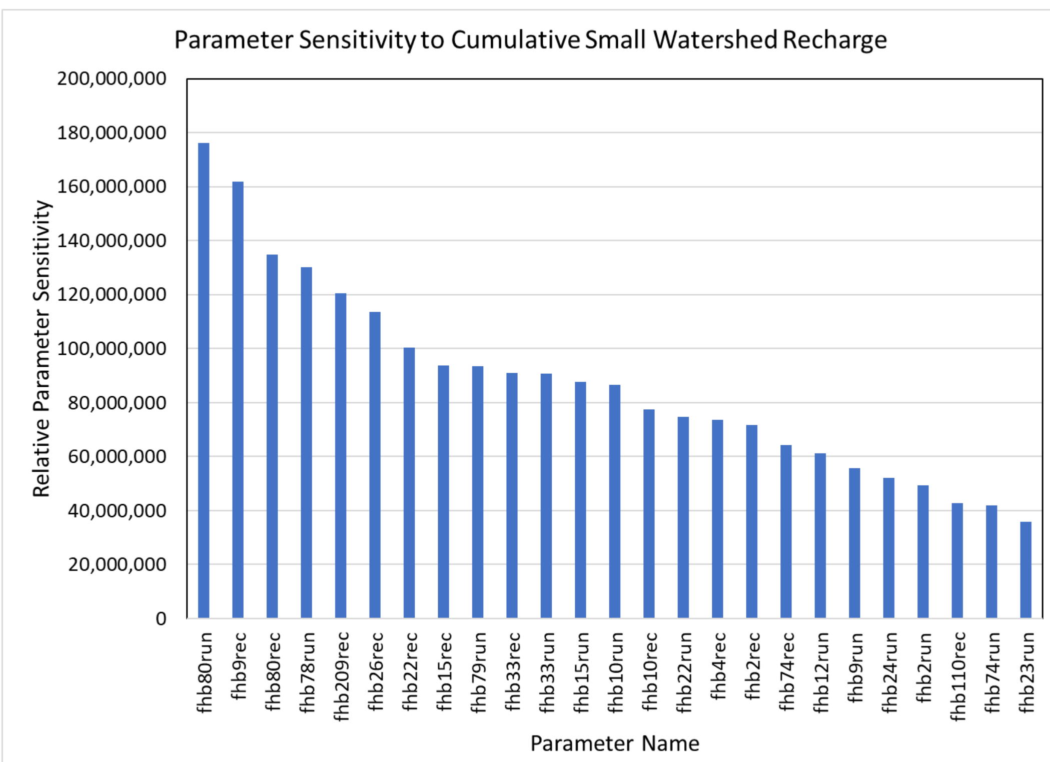
400,000,000
350,000,000
300,000,000
250,000,000
200,000,000
150,000,000
100,000,000
50,000,000
0
kc_d_gw
lua_perm
kc_w_gw
kc_n_gw
k_skinf
lua_rice
eftul16
efsac17
eff70tul
eff00tul
kc_d_ng
lua_viny
lua_pas2
lua_fild
eff70sac
eff00sac
eff90sac
lua_cott
eff80tul
efsac16
eff90tul
efsje16
eftul18
kc_w_ng
eftul11
Parameter Name

(d)


Parameter Sensitivity to Cumulative Recharge
Relative Parameter Sensitivity
200,000,000
180,000,000
160,000,000
140,000,000
120,000,000
100,000,000
80,000,000
60,000,000
40,000,000
20,000,000
0
eftul16
lua_perm
efsac17
kc_d_gw
eff70tul
lua_rice
eff00tul
efsac16
eff70sac
efsje16
k_skinf
kc_w_gw
eff00sac
eff90sac
rop_nat
kc_n_gw
eff80tul
eff90tul
lua_fld
eff80sac
eftul11
eff00sje
eff70sje
lua_pas2
eff90sje
Parameter Name

(e)


Parameter Sensitivity to Cumulative Small Watershed Recharge
Relative Parameter Sensitivity
200,000,000
180,000,000
160,000,000
140,000,000
120,000,000
100,000,000
80,000,000
60,000,000
40,000,000
20,000,000
0
fhb80run
fhb9rec
fhb80rec
fhb78run
fhb209rec
fhb26rec
fhb22rec
fhb15rec
fhb79run
fhb33rec
fhb33run
fhb15run
fhb10run
fhb10rec
fhb22run
fhb4rec
fhb2rec
fhb74rec
fhb12run
fhb9run
fhb24run
fhb2run
fhb110rec
fhb74run
fhb23run
Parameter Name

(f)

Figure S12. CVHM2 parameters that contribute most to the uncertainty in predicted (a) change in storage from specific yield, (b) change in storage from subsidence, (c) groundwater and surface-water interaction, (d) groundwater pumping, (e) groundwater recharge, and (f) small watershed recharge. Parameter names and descriptions are found in table 7 of the CVHM2 model release [59].