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A method for physically based model analysis of conjunctive use in response to potential climate changes

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[1] Potential climate change effects on aspects of conjunctive management of water resources can be evaluated by linking climate models with fully integrated groundwater–surface water models. The objective of this study is to develop a modeling system that links global climate models with regional hydrologic models, using the California Central Valley as a case study. The new method is a supply and demand modeling framework that can be used to simulate and analyze potential climate change and conjunctive use. Supply-constrained and demand-driven linkages in the water system in the Central Valley are represented with the linked climate models, precipitation-runoff models, agricultural and native vegetation water use, and hydrologic flow models to demonstrate the feasibility of this method. Simulated precipitation and temperature were used from the GFDL-A2 climate change scenario through the 21st century to drive a regional water balance mountain hydrologic watershed model (MHWM) for the surrounding watersheds in combination with a regional integrated hydrologic model of the Central Valley (CVHM). Application of this method demonstrates the potential transition from predominantly surface water to groundwater supply for agriculture with secondary effects that may limit this transition of conjunctive use. The particular scenario considered includes intermittent climatic droughts in the first half of the 21st century followed by severe persistent droughts in the second half of the 21st century. These climatic droughts do not yield a valley-wide operational drought but do cause reduced surface water deliveries and increased groundwater abstractions that may cause additional land subsidence, reduced water for riparian habitat, or changes in flows at the Sacramento–San Joaquin River Delta. The method developed here can be used to explore conjunctive use adaptation options and hydrologic risk assessments in regional hydrologic systems throughout the world.

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1. Introduction

[2] Climate change is likely to have important influences on water-resources management options that will be needed to sustain groundwater by conjunctive use strategies [*Alley et al.*, 1999; *Alley*, 2001]. In most watersheds, groundwater resources are really part of a single resource comprising precipitation, surface water, and groundwater resources that require combined simulation and analysis. Influences of climate change may be manifested as changes in streamflow in regions suitable for agriculture, and in the fundamental interplay between natural and societal water supplies and demands. With respect to groundwater, these climate-related changes may include significant variations in recharge, discharge, and groundwater withdrawals in concert with, and independently from, climatic influences on surface water resources. Many representations and considerations of these influences may have neglected the variations in near-term policy and operational decision making on seasonal to interannual time scales, and ignored the effects of climate changes on long-term policy and capital investment decisions on interdecadal time scales [*Gleick and Adams*, 2000; *Gleick et al.*, 2006; *Aerts and Droogers*, 2004; *Intergovernmental Panel on Climate Change* (*IPCC*), 2008; *California Natural Resources Agency*, 2009]. Some effects of climate change on agriculture have been addressed by previous studies [*Frederick et al.*, 1997; California Department of Water Resources (*CADWR*), 2005, 2008a; *U.S. Climate Change Science Program*, 2008; *Lettenmaier et al.*, 2008; *Karhl and Roland-Holst*, 2008]. Others have included these features but have not completely represented both components (surface water and groundwater) of conjunctive use and,

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especially, the role or effects of groundwater resources [*IPCC*, 1996; *Aerts and Droogers*, 2004; *Gleick et al.*, 2006; *Hanak and Lund*, 2008; *Chung et al.*, 2009]. Thus, a method to assess the short- and long-term perspectives is needed to understand how climate change may effect conjunctive use in a supply and demand framework to assess development, management, and sustainability of water resources [*Alley et al.*, 1999; *Alley*, 2001; *Alley and Leake*, 2004; *Gurdak et al.*, 2009; *Hanson et al.*, 2010b].

[3] Both climate change and variability along with increased human demand with potential land use changes will affect the distributions of supply and demand components [*Vörösmarty et al.*, 2010; *Aerts and Droogers*, 2004] and sustainable water development [*Scanlon et al.*, 2006] throughout the world's regional aquifers. Recent studies [*Hanson et al.*, 2002, 2004, 2006, 2009; *Gurdak et al.*, 2007, 2009; *Kumar and Duffy*, 2009] have identified quasiperiodic cycles in hydrologic time series of precipitation, groundwater, and streamflow that appear to correspond to quasiperiodic climatic forcings such as ENSO, NAMS, PDO, and AMO [*Dettinger et al.*, 1998; *Gurdak et al.*, 2009]. Additional recent studies also have indicated that climate change has started to affect the streamflow in regional watersheds of North America such as the Sierra Nevada and the Rocky Mountains [*Stewart et al.*, 2004, 2005; *Milly et al.*, 2005; *Barnett et al.*, 2008; *Das et al.*, 2009; *Gray and McCabe*, 2010], and has affected groundwater recharge such as in Sierra Nevada watersheds [*Earman and Dettinger*, 2008; J. L. Huntington and R. G. Niswonger, Role of surface and groundwater interactions on projected base flows in snow dominated regions: An integrated modeling approach, submitted to *Water Resources Research*, 2011] that provide runoff and recharge to the regional aquifers of the Central Valley, California.

[4] A method is needed to assess how climate change could affect surface water and groundwater use in highly developed agrourban watersheds. An emerging approach to providing this method is holistic modeling with conjunctive use analysis using linked and physically based hydrologic models that combine the natural and human components of use and movement of water. Some previous climate change studies have linked GCMs and regional hydrologic models at watershed scales with land uses such as agriculture [*Aerts and Droogers*, 2004; *Chung et al.*, 2009]. A few other studies linking GCMs to regional hydrologic models in historical contexts have included groundwater, surface water, and the demands of agriculture [e.g., *Hanson and Dettinger*, 2005]. However, there has not been a model linkage that has propagated potential forcings of climate change from the GCM global scale through the precipitation-runoff modeling of surrounding mountains and then to demand-driven and resource-constrained conjunctive uses of groundwater and surface water in an agricultural system such as the Central Valley of California. Previous studies have investigated portions of agricultural watersheds, such as the northern half of the Central Valley (Sacramento Valley), and investigated the demand from climate change on the regional surface water resources [*Aerts and Droogers*, 2004; *Chung et al.*, 2009] throughout the Central Valley. In contrast, this method employs a suite of models to obtain a physically based and realistically complex depiction of the whole conjunctive use system within a supply and demand modeling framework.

[5] Competing demands on water resources by urban, agricultural, and environmental stakeholders continue throughout the world [*Vorosmarty et al.*, 2010] and are especially exemplified by the history of water use and resource development in the Central Valley. California's water delivery system and agricultural practices have been designed and operated on the basis of the climate of the 20th century, yet the Central Valley's population has nearly doubled to 3.8 million people since the 1980s and is expected to increase to 6 million by 2020 [*Faunt et al.*, 2009d]. Regionally, urban growth has intensified demands for water that are exacerbated by expected reductions in Colorado River water deliveries to Southern California [*Faunt et al.*, 2009d], Statewide drought [*CADWR*, 2008b, 2008c], and the San Joaquin–Sacramento Bay Delta ecological crisis [*Faunt et al.*, 2009d]. During the historical period (1961–2003), surface water generally has been available with the major storage and supply systems in place, except during extreme droughts [*Faunt et al.*, 2009b]. The historical delivery of surface water represents 53% of the total water delivered for irrigation and municipal and industrial use, with groundwater pumpage making up the rest. Historical simulations [*Faunt et al.*, 2009a, 2009b, 2009c, 2009d] indicate that the full capacity for delivering groundwater has not been tapped since no more than about 61% of the potential simulated total in-place well-pumping capacity was required to supply the demand for water during the driest years of recent decades.

[6] As part of the ongoing U.S. Geological Survey Climate Change Program (http://www.usgs.gov/global_change/), the purpose of this study is to develop simulation and analysis methods. The assessment of the feasibility of these methods is demonstrated with the analysis of the effects of climate change on the Central Valley hydrologic system. This supply and demand modeling framework provides a method to evaluate a suite of linked models as part of the sort of decision support system that will be required for the analysis of conjunctive use in regional flow systems throughout the world. While the Central Valley example is used to demonstrate the capabilities of this method, this methodology is applicable to a wide variety of regional settings from the North China Plains, Indo-Gangetic basins [*Briscoe*, 2005] or Mediterranean basins, to the Blue Nile of Africa [*Jeuland*, 2010] and the Guranai of South America [*Foster et al.*, 2006].

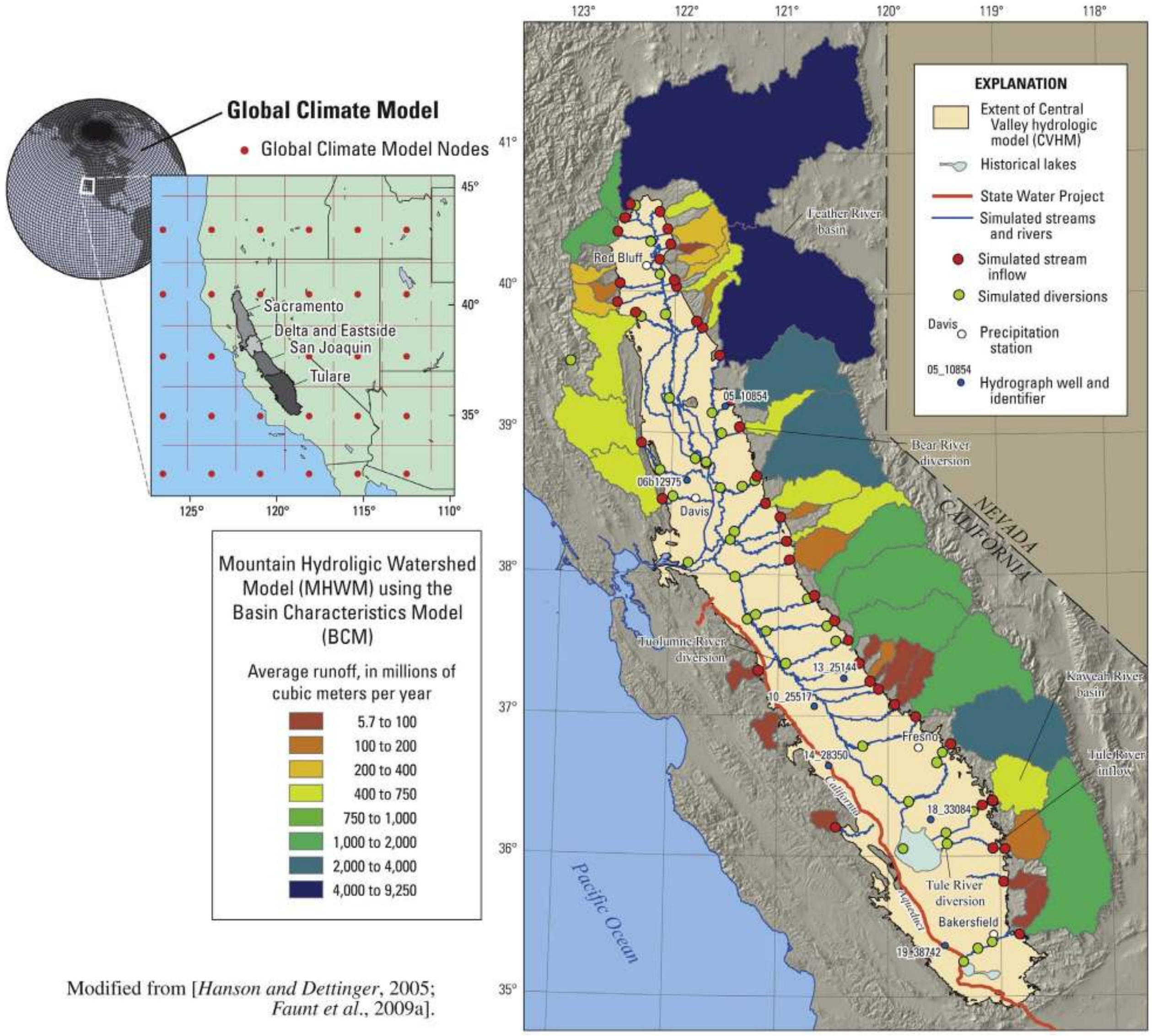
[7] In general, the present study is a step toward addressing several basic questions about the influence of climate change on conjunctive use of water resources: First, how does climate change and variability affect the availability and proportions of supply and demand components of agriculture? How do recharge, discharge, and change in storage in principal aquifers in the United States such as the Central Valley respond to climate variability on interannual to multidecadal timescales and to climate change from human activities? How much hydrologic response is caused by natural variability and how much is caused by human activities [*Gurdak et al.*, 2009]? Can the hydrologic responses projected by a series of linked physically based hydrologic models provide a tool for the management of demand-driven and supply-constrained conjunctive use?

[8] In this paper, we present the approach of this method by briefly describing the major components, including the downscaling of the climate change scenarios and the linkage

of the models. We demonstrate feasibility of the conjunctive use analysis from this method by presenting results from a GCM linked to a regional mountain hydrologic watershed model (MHWM) that provides inflow boundary conditions for an integrated hydrologic model of the Central Valley (CVHM) (Figure 1). The features available for simulation and analysis of the uses and movements of water include runoff from the surrounding mountains, the demands, uses and movements of water for irrigation and natural vegetation, and the response of supply from groundwater and streamflow under a climate change scenario. The potential effects of climate change simulated here include changes in diversions used to supply surface water for irrigation, streamflow and streamflow infiltration, groundwater storage, and related effects such as land subsidence and groundwater/surface water relations in the delta. Thus, groundwater, surface water, and agricultural components simulated by CVHM within the valley are inherently connected to the surrounding watersheds through runoff simulated by MHWM, therefore providing for a quantitative analysis of impacts on conjunctive use throughout the entire hydrologic system.

2. Approach to Regional Modeling

[9] GCM results were downscaled to a spatial resolution that is more commensurate with the complex terrain of



Modified from [*Hanson and Dettinger*, 2005; *Faunt et al.*, 2009a].

Figure 1. Map showing relation of global climate model (GCM) grid to areas of regional hydrologic models, to California, and to the Central Valley, California. Also shown are watersheds modeled with the mountain hydrologic watershed model (MHWM) by the basin characterization model (BCM) model and the active model grid for the valley-wide Central Valley hydrologic model (CVHM) with stream inflow that represents the linkage between the BCM and the CVHM models and diversion locations, selected precipitation and streamflow gaging stations, and wells. Modified from *Hanson and Dettinger* [2005] and *Faunt et al.* [2009a].

the CV watersheds and linked with regional hydrologic models. In so doing, it is possible to assess whether this methodology is a feasible approach to investigate potential effects of climate change on conjunctive use, not only in CV, but in other regional hydrologic systems. The order of modeling and linkage is (1) GCM simulation, (2) statistical downscaling over the extent of the regional hydrologic models (RHMs), (3) precipitation-runoff simulation of the regional watersheds surrounding the valley, (4) integrated hydrologic modeling of the valley, and (5) analysis of the multimodel output (Figure 2).

[10] The future climate projection used to demonstrate the method is the climatic response of a particularly greenhouse sensitive GCM, the Geophysical Fluid Dynamics Laboratory Climate model 2.1 (GFDL) [*Delworth et al.*, 2006], to a scenario of rapidly increasing greenhouse gas emissions (A2) [*Cayan et al.*, 2009; *IPCC*, 2007]. This particular climate scenario is generally characterized over California as quite warm and substantially drier than historical conditions. Climate projections such as the GFDL-A2 and related seasonal changes in precipitation and temperature in any given climate simulation only represent an example of the potential outcomes. Therefore, the MHWM and CVHM responses simulated here demonstrate the use of the method and do not represent particular events in the future; rather this example is a single sample from a distribution of possible hydrologic outcomes that, with consideration of additional scenarios (to come in future studies), could provide useful guidance for water resource management decisions.

[11] The MHWM model here is an implementation of the basin characterization model (BCM) [*A. L. Flint and Flint*, 2007; *L. E. Flint and Flint*, 2007a, 2007b], which is a grid-based distributed-parameter water balance model used to simulate evapotranspiration, changes in soil water storage, recharge, and runoff from precipitation in the surrounding watersheds of the Sierra Nevada on the eastern side of the Central Valley and selected parts of the Coast Ranges on the western side. The MHWM (BCM) was calibrated to reproduce historical streamflows for the period 1950–2000. The GCM predicted precipitation and temperature were used as input to MHWM (Figure 2). While other grid-based precipitation-runoff models could be employed for this part of the method such as the VIC [*Lettenmaier and Gan*, 1990; *Lettenmaier et al.*, 2008] or PRMS [*Leavesley et al.*, 1992; *Hay et al.*, 2000] models, the BCM

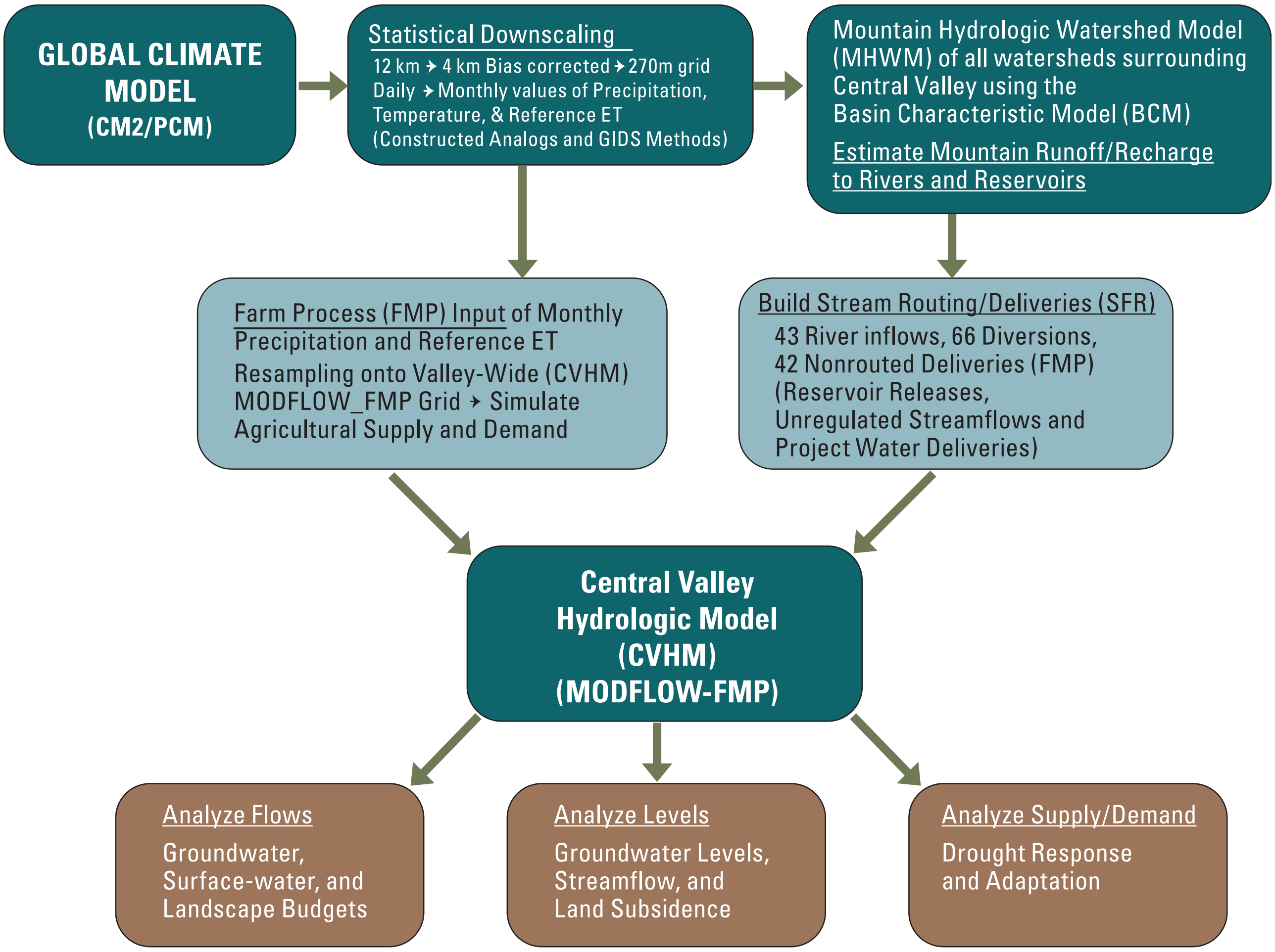


Figure 2. Diagram showing architecture of model linkages and data flow, used to simulate and analyze climate change, that constitute components of a decision support system for conjunctive use in the Central Valley, California.

provided adequate temporal detail and enhanced spatial detail that was efficiently computed for the large number of watersheds surrounding a large regional aquifer system such as the Central Valley.

[12] The CVHM is based on the integrated hydrologic flow model MODFLOW [*Harbaugh*, 2005] with the Farm Process (MF-FMP2) [*Schmid et al.*, 2006; *Schmid and Hanson*, 2009], and simulates integrated uses and movements of water throughout the landscape, surface water, and groundwater flow systems (Figure 1) [*Faunt et al.*, 2009a, 2009b, 2009c, 2009d]. The CVHM model was calibrated to historical hydrologic conditions for the period 1961–2003, to reproduce observed time series of streamflows, streamflow losses and gains, diversions of streamflow, land subsidence, and groundwater levels throughout the valley. CVHM is discretized with 10 layers of 2.59 km^2 square model cells and monthly stress periods and biweekly time steps [*Faunt et al.*, 2009c]. In this linked model methodology, the simulated reference ET, runoff and recharge from the MHWM, along with downscaled precipitation and reference ET derived from the GCM output, were then used as input to the Central Valley regional hydrologic model (CVHM) (Figure 2).

2.1. Linking Regional Hydrologic Models to a GCM

[13] The linkage of regional models to the GCM was a multistep and multipath process (Figure 2) that only used precipitation and temperatures from the GCM to describe climate change and represent the movement and use of water. Multiple steps were used to transform the GCM data to provide a feasible linkage through multiple paths to the RHMs (MHWM and CVHM) as regional monthly input that helps maintain separation between the supply and demand components of water use and groundwater/surface water responses to climate change. This method of linkage was unidirectional, in the sense that the larger scale models provide input to their finer-scale model partners, but are not affected by any feedback from the output of the finer-scale models. The methods and issues of linkage were discussed and analyzed for a historical period [*Hanson and Dettinger*, 2005] and for multiple watersheds with different hydrologic settings [*Aerts and Droogers*, 2004]. This method connects a GCM, which is globally energy and water balanced but not constrained through calibration by water transport to observed water transport, with the RHMs that represent more localized inflows and outflows that are both balanced and constrained through the calibration process with numerous local historical observations and observation types. Because the GCM is not specifically calibrated or adjusted for the detail of a regional watershed, downscaling with bias corrections are necessary to effectively transmit the GCM output to the RHM as input.

[14] The downscaling of GCM output is accumulated to monthly values from the constructed analogues [*Hidalgo et al.*, 2008] and gradient and inverse distance squared weighting (GIDS) methods [*Flint and Flint*, 2011]. The downscaling of precipitation and temperature data was a three-step statistical process (Figure 2) that started with the constructed analogues method [*Hidalgo et al.*, 2008]. First, the constructed analogues method is used to downscale GCM-simulated weather, day by day, from the GCM grid cells to a 12 km grid on the basis of the combinations of GCM scale observed, historical weather patterns that best reproduce the GCM-simulated weather for a given simulated day. The statistical downscaling method skillfully reproduces daily and, especially, monthly variations of precipitation and temperature deviations from long-term normals during the historical period, when applied to geographically smoothed (GCM-scaled) versions of the historical record [*Hidalgo et al.*, 2008; *Maurer and Hidalgo*, 2008]. The (RMSE) skill with which GCM patterns are reconstructed by constructed analogues during applications to GCM projections of future precipitation and temperature variations and changes does not decline as the 21st century proceeds, giving the primary basis for believing that the method continues to be skillfully applicable even under changing climatic conditions. Once this best fit combination of historical weather patterns is identified, the same combination of more finely resolved weather maps (for the same historical days) is constructed to obtain the downscaled (highly resolved) weather pattern corresponding to the GCM weather. Second, these constructed-analogues weather maps were then further downscaled to a 4 km grid using the GIDS method and bias corrected for long-term average and standard deviation differences between downscaled and observed statistics [*Flint and Flint*, 2011], which is an update to approaches used previously by *Aerts and Droogers* [2004] and *Hanson and Dettinger* [2005]. This downscaling step used a statistical interpolation approach developed by *Nalder and Wein* [1998] that was modified with a nugget effect specified as the length of the coarse resolution grid, in this case 12 km grid cell [*Flint and Flint*, 2011]. The model combines a spatial weighting with GIDS to monthly grid data by using multiple regressions developed for each month at each grid cell. Parameter weighting is based on location and elevation of the new fine-resolution grid (4 km) relative to existing coarse-resolution (12 km) grid cells [*Flint and Flint*, 2011]. The bias correction was then completed on a cell-by-cell basis for each month of the 100 year future climate scenario by matching means and standard deviations from the PRISM regional precipitation and temperature fields [*Daly et al.*, 1994] at each 4 km cell for the base period 1950–2000. This base period includes the IPCC base historical period 1970–2000 [*IPCC*, 2007, 2008].

[15] The third step is statistical downscaling to a finer spatial resolution that captures the resolution of the surrounding mountain watersheds and water balance subregions of the Central Valley example. This step uses the bias-corrected 4 km precipitation and air temperature data to downscale further to a 270 m grid for input to the MHWM with this same discretization using the GIDS approach. Downscaled precipitation and air temperatures at 270 m are used as the climate drivers to simulate runoff, recharge, and ET for the BCM in MHWM in the surrounding mountain watersheds, and then downscaled precipitation and reference ET are directly used as inputs for MF-FMP2 in CVHM to simulate water consumption of natural vegetation and crops, runoff back to streamflow networks, and deep percolation as groundwater recharge (Figure 2).

[16] It is important to recognize that this is a scenario, not a forecast and is used here to illustrate a plausible outcome and demonstrate the method of model linkage, feasibility of the supply and demand modeling framework, and

utility of conjunctive use analysis. The GCMs used in current climate change projections or even historical climate simulations are not constrained nor expected to reproduce the historical sequence of climatic events on any time scale short of the slow, specified time scale of the externally imposed greenhouse gas buildup. Given a large enough ensemble of such simulations (differing only in their initial conditions), the range of simulations may reflect (imprecisely) the range of possible alternative pathways along which historical climate could have evolved or, more practically, the range of uncertainties associated with the sensitive dependence of the climate (and climate model) on uncertain initial conditions, GCM to GCM differences, and continuing uncertainties about which emissions pathway society will choose to follow [*Dettinger*, 2005]. Particular components of the linked system also may have inherent uncertainties, such as those contained in streamflow projections [*Maurer and Duffy*, 2005], attributes of agricultural practices [*Ficklin et al.*, 2009], or assessment of risk in planning reservoir operations [*Brekke et al.*, 2009]. Therefore, the single (GFDL-A2) projection evaluated here can only be interpreted as one example from among a wide range of possible climate futures. The GFDL-A2 GCM simulation selected is one of the more extreme climate change scenarios among those available at the time of analysis [*Cayan et al.*, 2008], and can be considered a conservative estimate of the potential changes to the supply and demand components of a hydrologic system.

[17] In contrast, CVHM is an RHM that is tightly constrained by specified boundary forcings and conditions that require a constrained and calibrated regional water balance based on the match between historical observed and simulated water transport. Because of these strong constraints, historical simulations by RHMs, such as CVHM, can be calibrated to reproduce the historically observed fluctuations and magnitudes in groundwater levels, streamflow, land subsidence, and related water flow as closely as possible within the level of detail of the modeling framework [*Faunt et al.*, 2009c]. Even though RHMs, such as CVHM, are typically designed to be capable of being accurate at temporal and spatial scales relevant to the conjunctive use issues, uncertainties in measured inflows and outflows can typically range from 5% to more than 20% [*Hanson et al.*, 2002]. In turn, these uncertainties can result in several meters of model error in groundwater levels and related errors in estimates of changes in groundwater storage. When this is compounded with other local uncertainties driven by other climatic forcings such as tidal fluctuations at the delta, the resulting errors, even for calibrated models, can easily exceed a meter for groundwater levels at any given time or location. Even with these uncertainties, the CVHM model adequately reproduces the flow system, the long-term historical changes in flows and groundwater levels on a regional scale (root-mean-square error of groundwater heads of 0.24 m [*Faunt et al.*, 2009c]), and seasonal dynamic interactions in the conjunctive use and movement of water throughout the Central Valley [*Faunt et al.*, 2009c; *Hanson et al.*, 2010b].

2.2. Using the MHWM Model With GCMs

[18] The MHWM model used here is based on deterministic water balances that estimate in-place recharge, actual ET, and runoff according to the underlying BCM model [*A. L. Flint and Flint*, 2007; *L. E. Flint and Flint*, 2007a, 2007b]. The BCM model is grid based at 270 m and relies on gridded inputs of monthly precipitation, maximum and minimum air temperature. The model uses the distribution of precipitation, snow accumulation and melt, potential evapotranspiration, soil water storage, and bedrock permeability to calculate monthly water balances for the model area, including basin recharge and runoff over current and future climatic conditions. In this study, the MHWM application of BCM was driven by the downscaled GCM climate data to simulate actual ET, runoff, and recharge from the watersheds in the Coast Ranges and Sierra Nevada that provide inflows to the Central Valley (Figure 1).

[19] BCM computes potential evapotranspiration on an hourly time step on the basis of solar radiation that is modeled on the basis of percent of visible sky, accounting for topographic shading of each 270 m grid cell. Computed solar radiation, combined with maximum and minimum air temperatures, is converted to net radiation and soil heat flux [*Shuttleworth*, 1993]. The result is input into the Priestley-Taylor equation (equation (1)) [*Priestley and Taylor*, 1972] to estimate potential evapotranspiration (ET_p), taking into account vegetated and bare soil areas based on vegetation cover on a cell-by-cell basis [*A. L. Flint and Flint*, 2007].

$$\mathrm{ET}_P = \frac{S}{(S+\gamma)}(R_n - G)\lambda \tag{1}$$

where s is the slope of the vapor deficit curve, γ is the psychrometric constant, R_n is net radiation, G is soil heat flux, and λ is the heat of vaporization. The component $\frac{S}{(S+\gamma)}$ is a temperature-dependent function of the form

$$SSG = \frac{S}{(S+\gamma)} = -13.281 + 0.083864\,(T_a) - 0.00012375\,(T_a)^2 \tag{2}$$

where T_a = average monthly air temperature in degrees Kelvin.

[20] The projected (future) potential evapotranspiration (ET_p) relies on projected air temperature to scale the driving forces to current ET_p:

$$\mathrm{ET}_{p(\text{future})} = (SSG_{\text{f}}/SSG_{\text{c}})(\mathrm{ET}_{p\,\text{current}}) \tag{3}$$

where SSG_{c} and SSG_{f} are $\frac{S}{(S+\gamma)}$ for current climate and future climate, respectively, on the basis of mean monthly air temperature, T_a, for current climate or future projections. This ET_p is aggregated to monthly totals and used with precipitation, soil water storage, and bedrock permeability to determine areas where excess water is available. If available, the model determines whether the water can be stored in the soil, infiltrated into the underlying bedrock (at an estimated rate equivalent to the bedrock permeability), or routed away as runoff.

[21] In general, if a future month is warmer than the 1971–2000 "normal" month, then ET_p increases; if it is colder then ET_p decreases. This approach to estimating future ET_p assumes that R_n and G are the same in the

future as they are now, for which we have no reliable information at this time. Because *SSG* is nonlinear with temperature, areas with colder climates (e.g., northern Central Valley and Sierra Nevada) that increase in temperature with future climate have a greater increase in ET_p than warmer areas because the slope of equation (2) continually flattens out with increasing temperature.

[22] Snow accumulation and ablation are simulated by using an adaptation of the operational National Weather Service (NWS) energy and mass balance model; specifically, by using the Snow-17 model described by *Anderson* [1976] and *Shamir and Georgakakos* [2007]. The model calculates the potential for melt as a function of air temperature and an empirical snowmelt factor that varies with day of year [*Lundquist and Flint*, 2006]. The accumulated snow depth is calculated for areas where precipitation occurs and air temperature is less than or equal to 1.5°C (34.7°F). Sublimation of snow is calculated as a percentage of potential evapotranspiration on a monthly basis analogous to snow course data.

[23] In the historical (1962–2003) period, observed precipitation and temperatures were input to the BCM to simulate the potential runoff and recharge from the mountain watersheds that surround the Central Valley (Figure 1). Although the model is monthly, because of the disruption of the natural seasonal signal by reservoir operations, the model was calibrated to approximately reproduce annual measured runoff totals from below reservoirs at 43 stream inflow points. This calibration was a manual, iterative process that began by modeling small gauged upper watershed subbasins with no regulated flows owing to management or diversions to establish appropriate bedrock permeabilities for each of the bedrock types in the model. Bedrock permeability is the parameter that partitions excess water into runoff and recharge, with higher permeabilities resulting in greater recharge, and lower permeabilities resulting in greater runoff. Details and results of this calibration for the Great Basin Carbonate and Alluvial Aquifer System are discussed at length by *Flint et al.* [2011], along with model limitations and uncertainties. Upper watershed subbasin outflows were assumed to reflect only runoff conditions that have insignificant base flow. Recharge and runoff were then simulated for all 43 watersheds.

[24] Because the different basins have varying amounts of base flow because of the different geologic environments and alluvial deposits, further calibration was performed by adding in-place recharge to runoff estimates until observed yearly outflows were matched. For example, the Sacramento River basin is bounded by volcanic rocks that produce large amounts of groundwater-fed base flow, and as a result, all of the recharge calculated for that basin was added to the runoff in the final calibration. In contrast, the basins in the granitic terrains of the central Sierra Nevada are runoff dominated, and no estimated recharge was added to the basin outflow to match the measured streamflow data. The calibration was done by using annual data, without regard to the timing differences owing to seasonal management operations that are reflected in the monthly observations. The calibration results for the 43 basins, when comparing measured and simulated annual basin discharge for 1962–2003 are reasonable and provide confidence in the calibration. The average ratio of the total measured discharge to simulated discharge was 1.00, and the average ratio of the log of the total measured discharge to simulated discharge was 0.991. The Nash-Sutcliffe efficiency statistic [*Nash and Sutcliffe*, 1970] (1 minus average mean square error divided by variance) was 1.00 and the average r^2 of the measured versus the simulated annual discharge was 0.746.

[25] A final step was taken that scaled the simulated basin discharge to better match the reservoir outflows, accounting for losses in the system owing to diversions or agriculture, or gains to the system owing to subsurface flows from larger, higher-elevation basins to adjacent smaller basins that are downslope. A potential uncertainty in the impacts of climate change on conjunctive use is with regard to the future reservoir operations that are the linkage point between the outflows from the mountain hydrology simulated with MWHM and stream inflows in the Central Valley simulated with CVHM. The MHWM currently does not explicitly simulate rules for reservoir operations but instead uses a scaling approach to match current flows below the reservoirs that approximate annual influences of the reservoir on the water delivered from the mountain watershed to the valley. These same scaling factors are applied to the future climate flows as well, making the assumption that reservoir operations will not significantly change with changes in climate. No water allocation models adequate to providing the linkages and operating rules for all of the reservoirs around the Central Valley were available for this study. However, where regulated flows from reservoir operations provide a significant influence over inflows, this additional linkage may be required to improve the skill of the projections.

[26] Monthly runoff and recharge were simulated for 2000–2100 for all watersheds surrounding the Central Valley and accumulated for drainage areas above each of the stream inflow locations. The monthly accumulated runoff and recharge simulated with MHWM from the watersheds surrounding the Central Valley become the inflows to the CVHM simulation of streamflow routing throughout the Central Valley (Figure 1).

2.3. Using the CVHM Model With GCM and MHWM

[27] To demonstrate the linkage with the GCM and MHWM to CVHM simply requires monthly downscaled GCM climate data over the valley floor and simulated stream inflows from the MHWM model. The downscaled monthly precipitation and potential reference evapotranspiration (Priestley-Taylor approximation, equation (3)) are used as inputs for the Farm Process within MF-FMP2 [*Schmid and Hanson*, 2009] on a cell-by-cell basis to drive consumption of water and runoff across the modeled landscape of the Central Valley from irrigated agriculture as well as from natural and urban vegetation (Figure 2). The CVHM simulates the streamflow, consumption of water as well as runoff and return flows across the landscape, the pumpage of groundwater to supplement surface water deliveries for irrigation, urban water supply pumpage and the effects of groundwater pumpage as land subsidence. Potential effects of increased CO_2 concentrations in the atmosphere on crop water demand coefficients are not included in this study. Similarly, agricultural and urban land uses were held fixed at year 2000 conditions [*Faunt et al.*, 2009a,

2009b, 2009c, 2009d]. Thus, only the direct effects of climate on agricultural and water resources are demonstrated with this example of the supply and demand modeling framework.

[28] The monthly runoff from the surrounding watersheds simulated by the MHWM became stream inflows at 43 locations in the CVHM, where it was routed through the streamflow network throughout all of the major rivers and related conveyance of water to the 66 diversions and exits the valley at the delta (Figure 1). The downscaled precipitation over the valley floor from the GFDL-A2 scenario was used to classify wet, variable-to-dry, and dry year periods from the cumulative departure of future precipitation at Davis, California (Figure 1) and are shown in time series graphs as background shading (Figure 3). As in the work by *Hanson and Dettinger* [2005], each potential future diversion and nonrouted delivery (NRD) was specified for each month on a potential delivery based on future climatic periods and the historical monthly climate-based deliveries. The CVHM simulates supply-constrained demand because these assigned diversions are also dependent on whether the amount of water that enters from the upstream watershed provides enough water to satisfy any or all of the specified diversion after routing the water from the mountain watershed. The diversions take any water that is available up to the specified amount, and the FMP then demands water from the point of diversions to be delivered from one or more diversions to each water balance subregion on the basis of the demand for irrigation from local agriculture in 21 water balance subregions. The NRDs are delivering the full amount specified and their conveyance is not simulated.

[29] The conjunctive use of surface water deliveries and groundwater within CVHM are demand driven and supply constrained on the basis of the physical movement and use

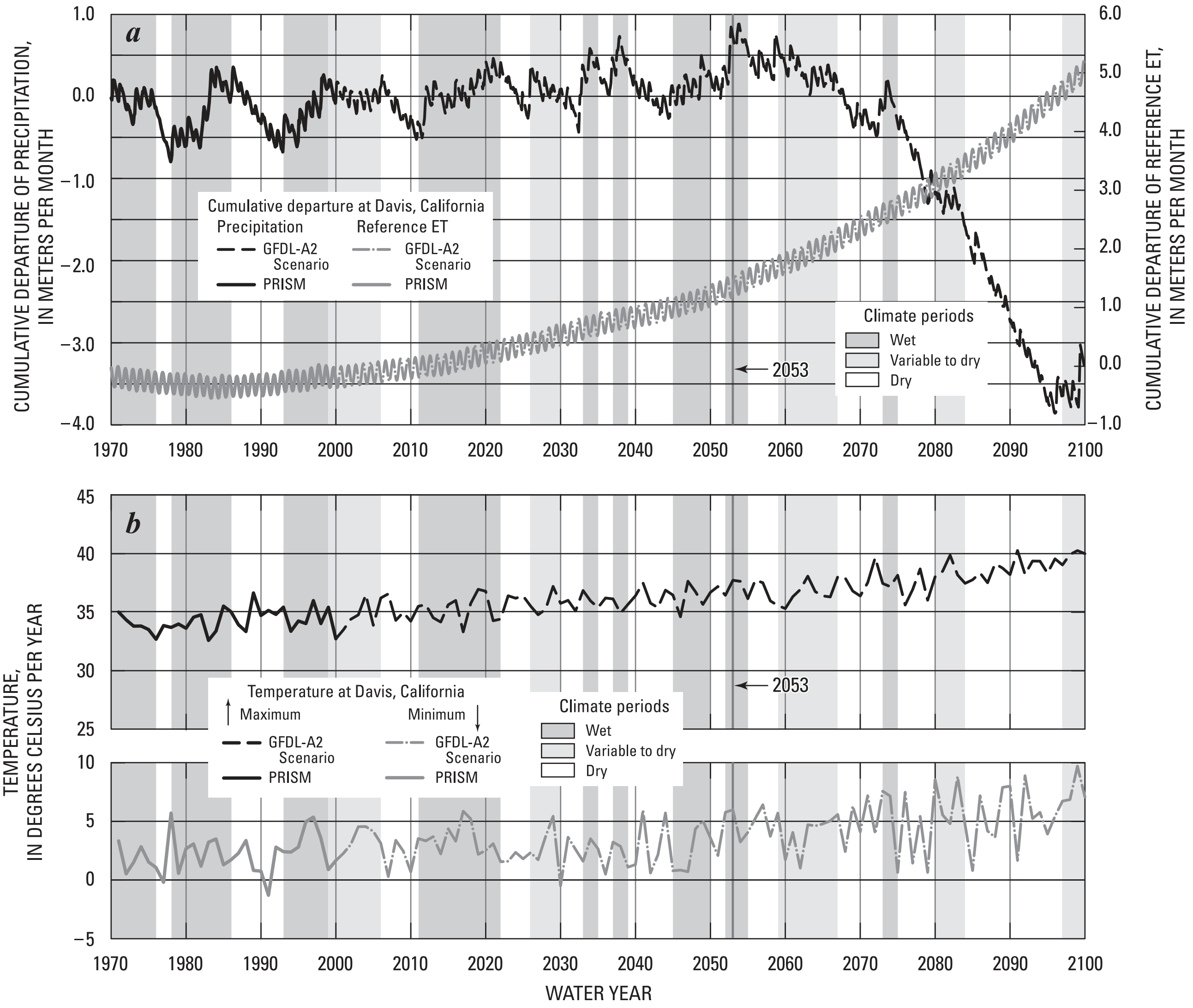


Figure 3. Graphs showing (a) historical and future cumulative departure of monthly precipitation and evapotranspiration (ET) and (b) monthly historical and future cumulative departure of temperature, (c) historical and selected future streamflow percentages, (d) selected historical and future streamflow, and (e) discharge, for selected decades, from the principal surrounding watersheds of the Central Valley, California.

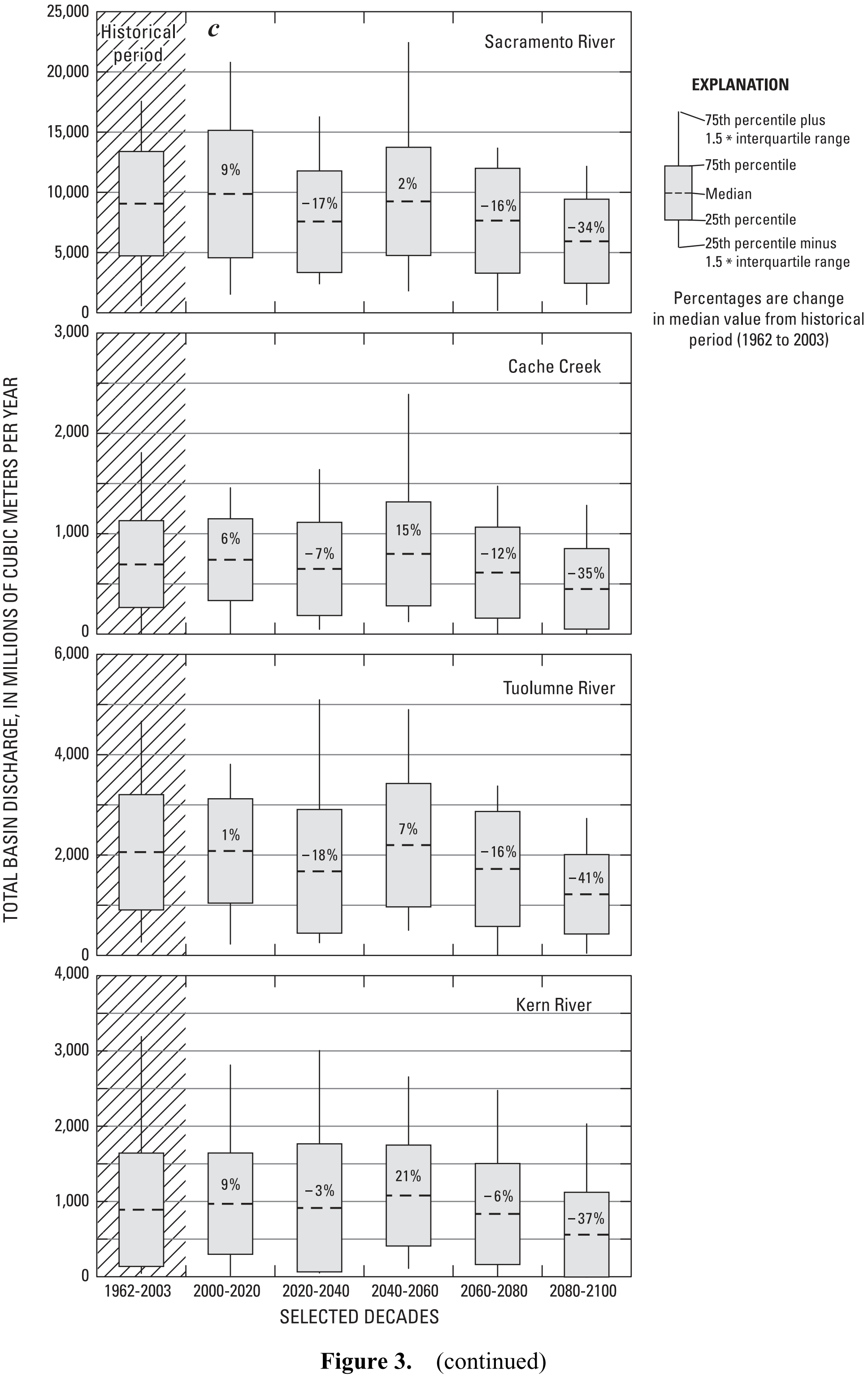


Figure 3. (continued)

of water simulated with MF-FMP2. The supply and demand framework starts with estimation of demand for water as the actual ET from irrigated agriculture and natural vegetation throughout the valley floor. Actual ET is the product of the downscaled reference ET (ET_p) and crop coefficients on a cell-by-cell basis that are scaled by fractions of land exposed to bare soil evaporation and to transpiration for each crop type. The crop irrigation requirement (CIR) is the demand for water that is needed to satisfy the actual ET after potential consumption of precipitation and direct uptake from groundwater. The crop irrigation requirement (CIR), deep percolation to groundwater, and runoff back to streams is then simulated with the additional use of irrigation efficiencies and fractions of inefficient loss of water to runoff on a cell-by-cell basis. Thus the CIR and irrigation efficiencies on a cell-by-cell basis

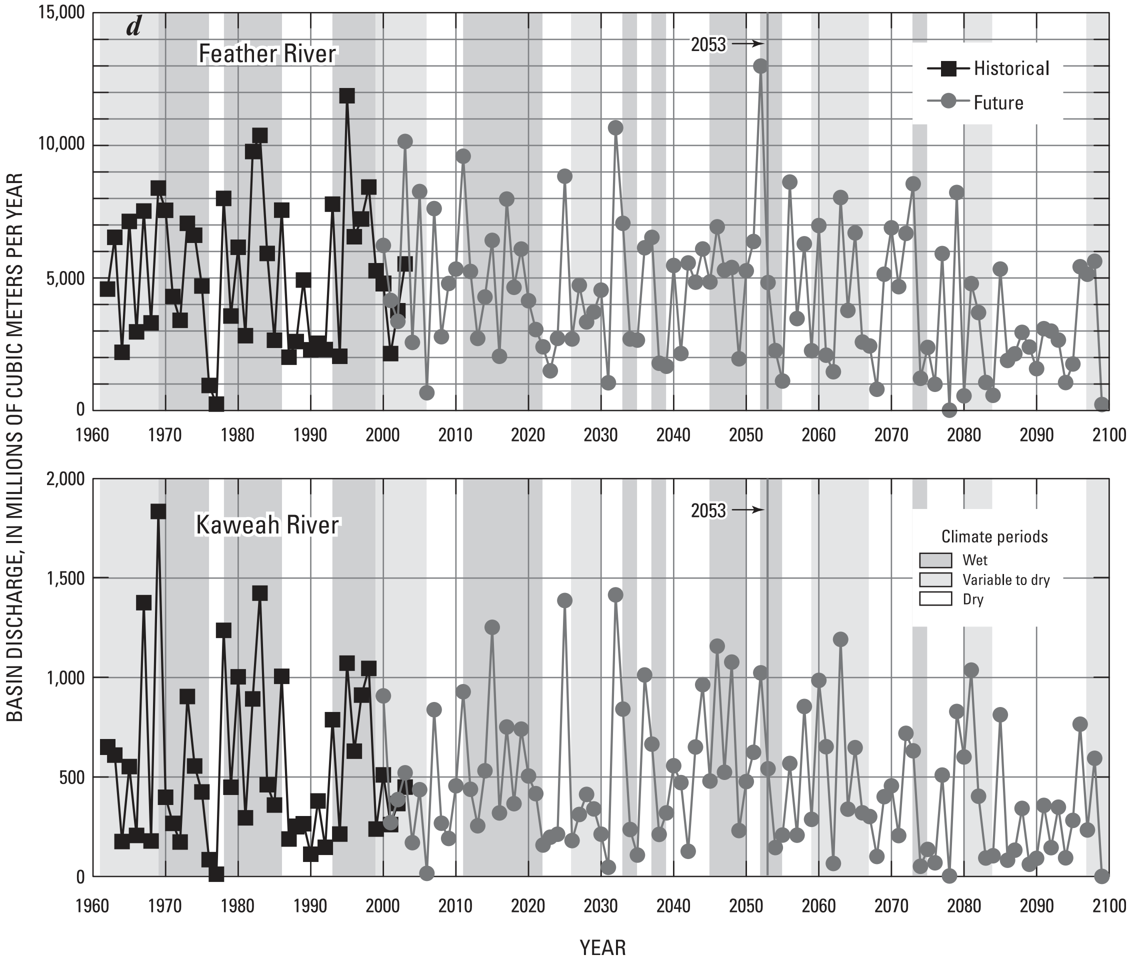


Figure 3. (continued)

dictate the collective Total Farm Delivery Requirement (TFDR) that is needed to satisfy the irrigation demand for each of the water balance accounting subregions. Groundwater recharge and runoff to streams is then computed as fractions of the inefficient losses from precipitation and irrigation. The irrigation demand for surface water is the first supply component of the TFDR. These demands are constrained by the potential climate-based diversions and by the actual amount of water routed through the streamflow network that is available to achieve the potential diversions. If surface water deliveries do not satisfy irrigation demand, then the TFDR demand is supplemented with additional supply from groundwater pumpage. The future scenario demonstrated here used deficit irrigation that would reduce demand to the available supply if demands exceed the capacity to supply irrigation. However, an operational drought, where demand exceeds the collective capacity of surface water deliveries supplemented with groundwater pumpage, was never achieved in this future scenario because of the excessive capacity to pump groundwater.

[30] To complete the linkage with climate, the model also simulates the potential groundwater outflow or inflow as well as river outflow at the delta. Boundary groundwater levels that control the groundwater outflow at the delta were changed on a monthly basis to reflect the rising sea level. The overall rise in sea level for San Francisco Bay was estimated to be as much as 0.86 m (3.1 feet) for the GFDL-A2 scenario [*Cayan et al.*, 2008].

[31] Increase in urban water demand for this example was an assumed linear 1.2% annual increase in urban water use based on a statewide projection for the period 2008–2025 [*Johnson*, 2009]. This increase was imposed directly onto the distribution of urban wells from the year 2000 and reflects an increase in urban water use without a change in urban land use. This projected increase in urban demand is less than half of the 4% increase from the recent past (1983–2003) used for the historical calibration of CVHM [*Faunt et al.*, 2009a, 2009b, 2009c].

3. Results

[32] The feasibility of the supply and demand modeling framework and how this method can provide insight into primary and secondary effects of climate change on conjunctive use within regional hydrologic systems is demonstrated through the linked models of the Central Valley, California. Given a set of linked global climate, regional downscaled climate and regional and local hydrologic models such as described here, the response and sensitivity of a given regional hydrologic system to possible climate changes can be used to evaluate the conjunctive use of

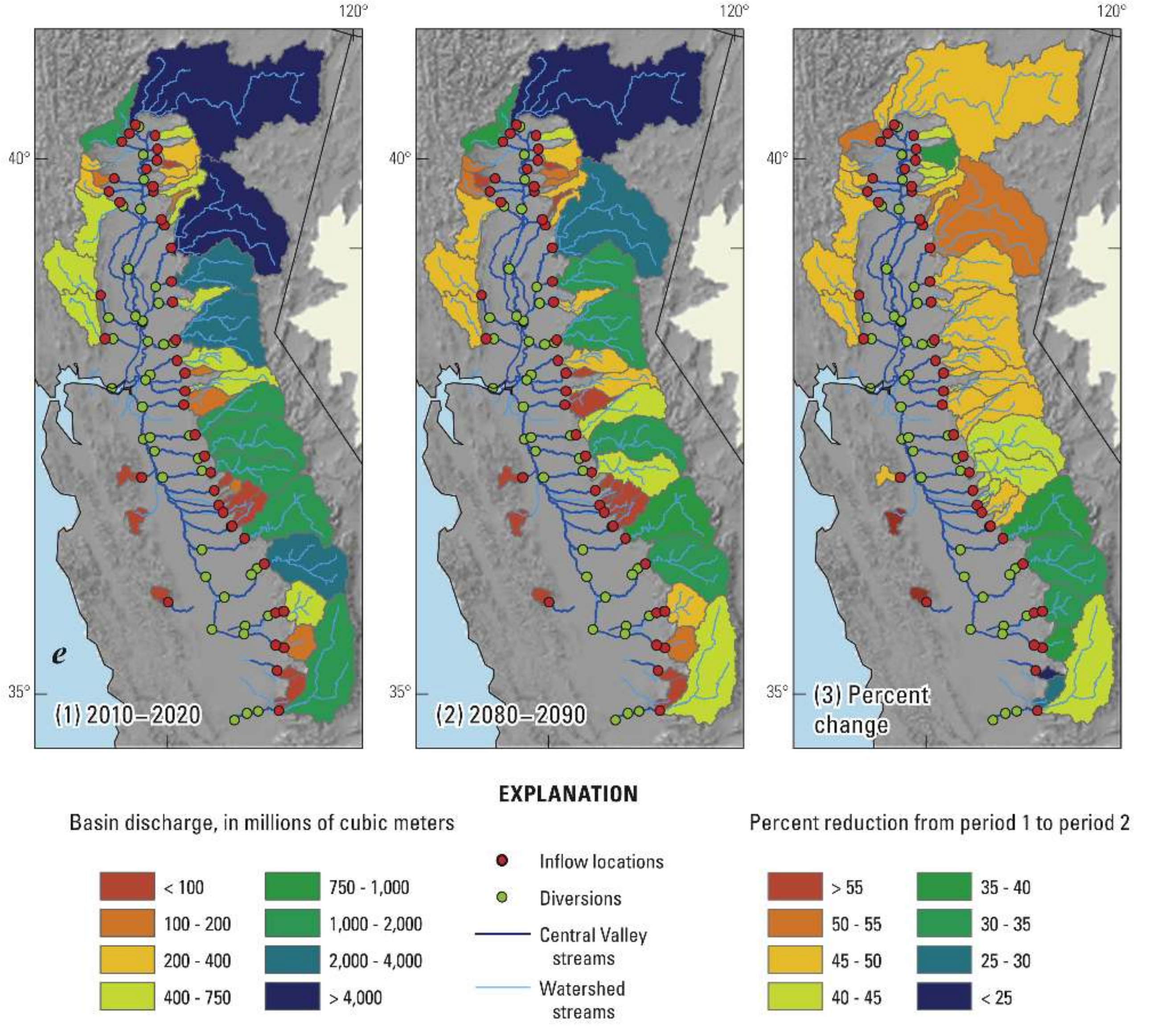


Figure 3. (continued)

water where complex hydrologic and agricultural supply and demand interact.

[33] The downscaled GCM precipitation and temperatures from the GFDL-A2 climate change scenario drive the supply and demand components of this modeling system. The models react to the reduced supply of water with reduced precipitation and related runoff to streamflow, as well as increased demand for irrigation and water available for runoff through reduced precipitation and increased ET*p* from increased temperatures. Overall the precipitation includes intermittent climatic droughts in the first half of the century and sustained droughts in the second half (Figure 3a). Over the 2000–2100 simulation, 57 years are below average precipitation, with 15 years less than and 15 years more than one standard deviation from the mean, respectively. Twelve of these pronounced dry years occur in the second half the 21st century GFDL-A2 scenario, with some average to dry periods lasting more than a decade. Minimum and maximum temperatures from the GFDL-A2 mean increase by approximately 5.4°C and 7.3°C, respectively, from 2000 to 2100 (Figure 3b). Accordingly, cumulative departures of ET_p that historically lack any significant trend [*Hidalgo et al.*, 2005], increase at an accelerating pace through the 21st century driven by increasing temperatures (equation (2) and Figure 3a).

[34] The supply and demand framework reacts to reductions in runoff from the MHWM model and significantly reduces the surface water supply linkage to CVHM that, in turn, shifts the agricultural system into substantial reliance on groundwater pumpage. The simulated changes in climate result in substantial declines in the flows draining into the Central Valley from surrounding mountain watersheds simulated with MHWM, with up to 40% declines in discharge at many of the CVHM inflow points by the end of the 21st century (Figure 3c). This scenario is consistent with recent climate change effect estimates of reduced discharge of 16%–34% during droughts in the 21st century for the Rocky Mountains [*Gray and McCabe*, 2010] but is

higher than most previous estimates for the Sierra Nevada [*Gleick*, 1987; *Lettenmaier and Gan*, 1990; *Jeton et al.*, 1996; *Knowles and Cayan*, 2002]. Annual time series of discharges from the Feather and Kaweah River uplands illustrates the generally prevailing trend in this scenario toward a moderate decline by the end of the century, but more notable increases in frequency of lower streamflows and related dry years in the latter half of the 21st century (Figure 3d).

[35] The linked models yield overall reductions in surface water deliveries for irrigation to the regions adjacent to the Sierra Nevada that show the greatest impact of the simulated transition in sources of supply to meet climate-driven increases in agricultural demand. The projected spatial distribution of mean basin discharge for two selected decades (2010–2020 and 2080–2090) indicates reduction of the inflows to CVHM by 20% to 65% with the largest reductions in the northern Sierra Nevada (Figure 3e). This is consistent with previous studies that showed the largest decrease in snow-water equivalent in the north [*Knowles and Cayan*, 2002] because the northern Sierra Nevada is lower and warmer and thus is more susceptible to warming in the near term future (most of this century, at least). The cooler colors indicate more total basin discharge (Figure 3e, maps 1 and 2), correlating in most cases with the size of the basin, and indicating that most of the discharge comes from the northern basins. Near the end of the 21st century, the potential total basin discharge contributing to the Central Valley water supply has declined by over 45%. Thus, the detail of MHWM allows delineation of all of the mountain watersheds and related reductions that affect the large northern watersheds that feed into the Sacramento Valley, which is historically a larger user of surface water [*Faunt et al.*, 2009a, 2009b, 2009c].

[36] The modeling framework exemplifies the types of conjunctive use relations that are a direct outcome of separation of the supply and demand components from cell-by-cell estimation of crop and native vegetation consumption combined with regional, physically based supply within a fully integrated hydrologic simulation. For example, the GFDL-A2 climate projection drives changes in the MHWM runoff and recharge that result in reductions in water supply to the Central Valley as streamflow for irrigation, water supply, and ecological uses, as well as reductions in groundwater recharge. This decline results in reduced streamflow diversions for irrigation and riparian habitat uses (as indicated by the potential for reduced inflows and more intermittent diversions on the Tule River; Figure 4a) in the Tulare Basin, reduced diversions on the Tuolumne River (Figure 4b) in the San Joaquin Basin, and reduced diversions on the Bear River (Figure 4c) in the Sacramento Valley. As surface water diversions are reduced, demands for groundwater pumpage increase to compensate, and groundwater levels are affected. A 50% reduction in recharge from streamflow infiltration (Figure 4c) on the Central Valley also adversely reduces groundwater levels. Relative to the historical period (1961–2003), deep percolation from precipitation and irrigation increases by about 4%, but this is a small component of the 3.5 times increase in storage depletion from increased pumpage. The small increase in net recharge is caused by a combination of increased irrigation and reduced ET uptake directly from groundwater.

[37] Climate and agriculture are linked through increased irrigation demand. This is exemplified by the GFDL-A2 scenario where the amount of actual ET increases with increased ETp and decreases in precipitation. For the historical period 1961–2003, total delivery requirements for agriculture ranged between 18,500 and 28,400 $\mathrm{hm}^3\ \mathrm{yr}^{-1}$ (15–23 MAF yr^{-1}, where MAF is million acre-feet, $1.233 \times 10\ \mathrm{m}^3$), with a modest decline through time that may have reflected increasing irrigation efficiencies. Under the first 50 years of the GFDL-A2 scenario, total delivery requirements continued to decline generally, with increases during intermittent droughts, ranging from 21,500 $\mathrm{Hm}^3\ \mathrm{yr}^{-1}$ (17.4 MAF yr^{-1}) to 17,800–25,300 $\mathrm{Hm}^3\ \mathrm{yr}^{-1}$ (14.4–20.5 MAF yr^{-1}) (Figure 5a). This is comparable to the historical average and range, and is about 9% less than the average TFDR for the entire 21st century projection. However, in the second half of the 21st century under the GFDL-A2 scenario, sustained droughts and more persistent dry conditions drive demand to about 50% larger increases than the range of historical demand fluctuations, increasing to as much as 30,800 $\mathrm{Hm}^3\ \mathrm{yr}^{-1}$ (25 MAF yr^{-1}) by the end of the 21st century (Figure 5a). Thus, the supply and demand method quantifies the total water delivery requirements (TFDR) for agriculture and the proportions of surface and groundwater supplies used to meet them.

[38] The modeling framework allows us to simulate the temporal and spatial transition of conjunctive use from predominantly surface water to groundwater deliveries for its irrigation supplies during persistent droughts driven by climate change. The historical modeled proportion of surface water to groundwater deliveries was about 2 to 1 for wet periods and about 1 to 3 during persistent dry periods, averaging about 1.33 to 1 overall. In contrast, the GFDL-A2 scenario yields modeled ratios of surface water to groundwater deliveries that average about 1 to 2.75, and ranging from 1 to 1 during wetter periods to about 1 to 3 during dry epochs. This partitioning between supply sources drastically changes under the effects of the persistent droughts and warm temperatures of the second half of the 21st century. By the end of the century, the fractions are consistently 1 to 3 or lower in favor of predominantly groundwater supplies (Figure 5a). The overall delivery requirements also increase to annual volumes that are more than the demand prior to the regular delivery of State and Federal project water. Combined with this change in sources is a 20% increase in actual ET from applied water that also reflects an overall 3.3% increase in overall actual ET combined with a 10% reduction in actual ET from reduced precipitation and a 61% reduction in actual ET directly from groundwater between the first and second half of the 21st century.

[39] The modeling framework also facilitates the analysis of changes in streamflow gains and losses through river beds into the Central Valley's groundwater system that are altered with climate change. The GFDL-A2 scenario yields decreases in net riverbed infiltration all over the Central Valley (Figure 5b). The streamflow base flows in the Sacramento Valley are diminished and then stop, and the rates of infiltration from the rivers of the San Joaquin Valley increase during the second half of the 21st century (Figure 5b). Overall the nature of net riverbed infiltration has changed from the simulated historical distribution for the period 1961–2003, and may result in reduced and more variable surface water flows in the delta.

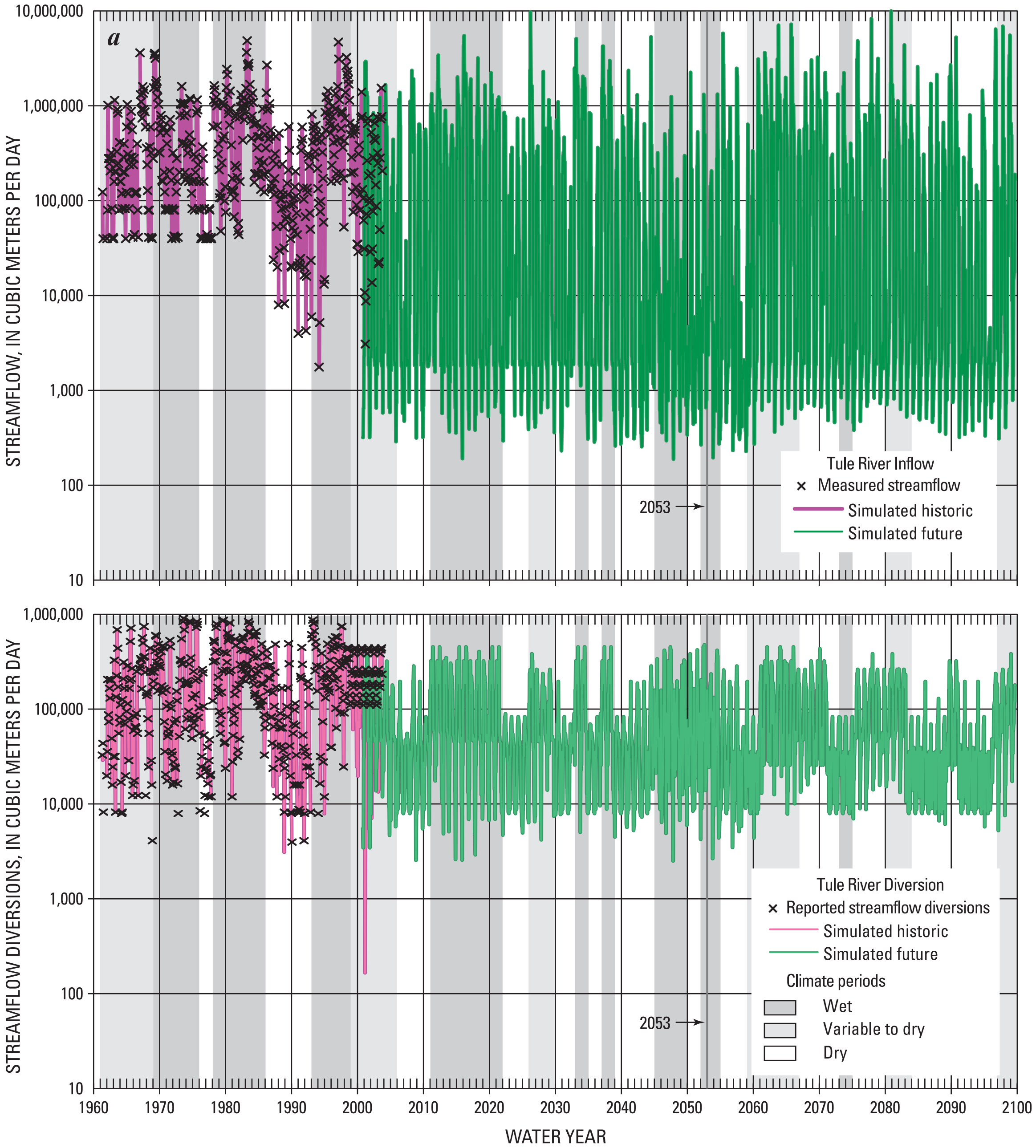


Figure 4. Graphs showing historical and future hydrologic response with the GFDL-A2 scenario of (a) stream inflow and diversions for riparian habitat along the Tule River in the Tulare Basin, (b) diversion along the Tuolumne River for riparian habitat streamflows in the San Joaquin River Basin, and (c) diversion from the Bear River in the Sacramento Valley, Central Valley, California.

[40] The integrated approach to supply and demand demonstrates the transition to a groundwater-based agricultural system with some of the largest effects from the change in climate related to the changes in groundwater storage. Future accelerated storage depletions are driven by climate-induced increases in groundwater demands by agriculture (with no change in land use or land cover) and municipal needs (with an assumed 1.2% urban growth) and the persistent droughts at the end of the century (Figure 5c). The historical simulation of 1961–2003 yielded substantial groundwater storage depletions of almost 86,300 Hm^3 (70MAF) that was especially large in the southern part of the valley called the Tulare Basin [*Faunt et al.*, 2009a, 2009b, 2009c]. In contrast, the future GFDL-A2 scenario yields additional storage depletions of about 113,500 Hm^3 (92 MAF) in the first half of the century followed by depletions of 235,600 Hm^3 (191 MAF) in the latter half.

[41] The simulation of agricultural irrigation from multiple aquifers within an integrated hydrologic model demonstrates that groundwater level declines do not occur everywhere, and occur differently depending on locations and depths below land surface of the pumped aquifers and distribution of multiaquifer wells (Figures 4c and 6). Simulation of conjunctive use shows how water level declines in

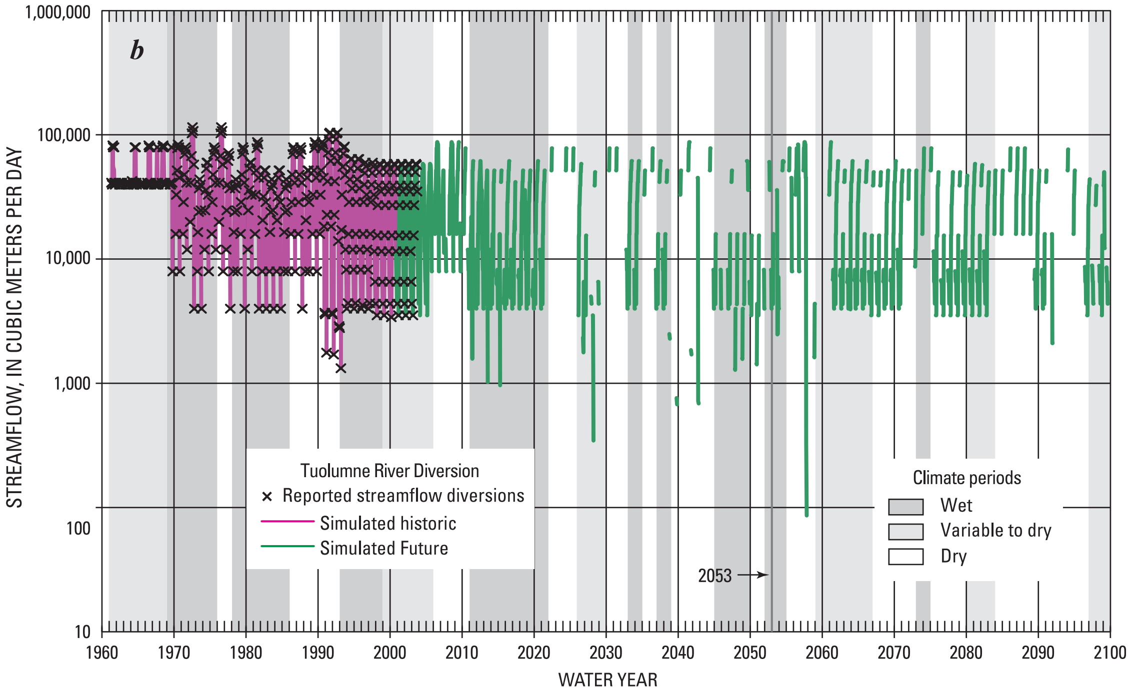
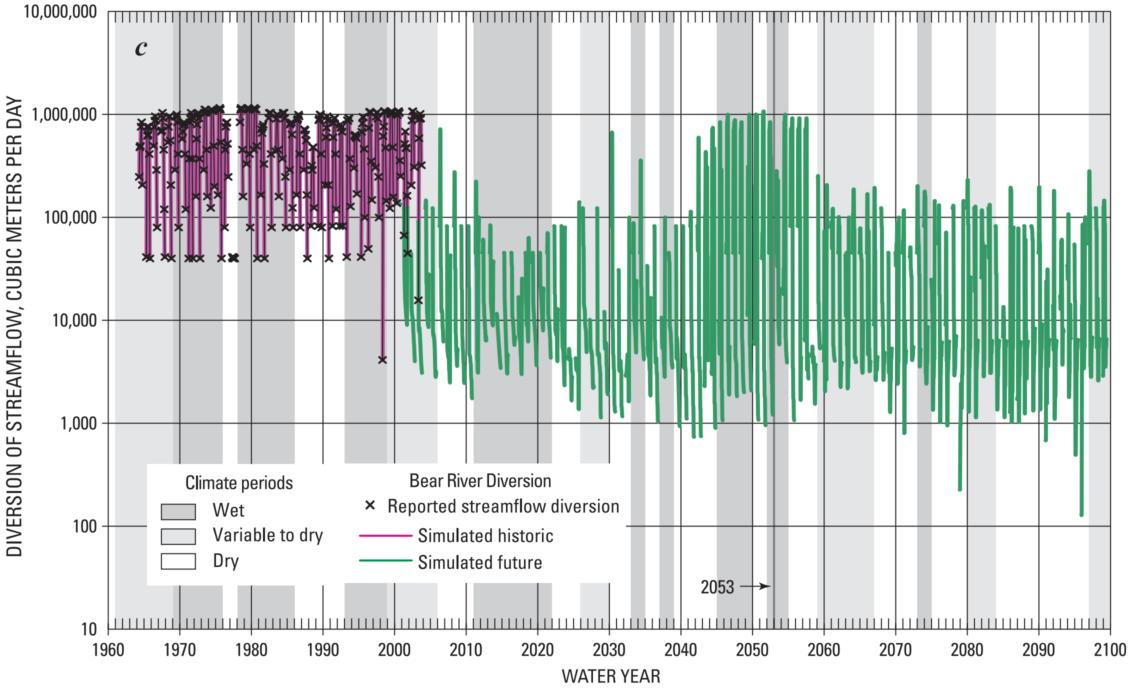


Figure 4. (continued)

the shallower aquifers of the Sacramento Valley are dampened in some places by reductions in leakage into streams, whereas other areas show water level declines of tens of meters caused by the increased pumpage required to offset reduced surface water deliveries for irrigation (Figures 4c and 6a). Similar declines are present in wells screened below the Corcoran Clay (well 13_25144 and 14_28350) but some of the wells screened in the shallower aquifers (well 10_25517) only start to show declines at the end of the sustained drought at the end of the 21st century (Figure 6b). These complex relations can only be discerned from our supply and demand modeling framework.

[42] In highly developed hydrologic systems, secondary effects such as land subsidence can become a limiting factor to sustained conjunctive use. While subsidence is relatively less in some of the original historical subsidence



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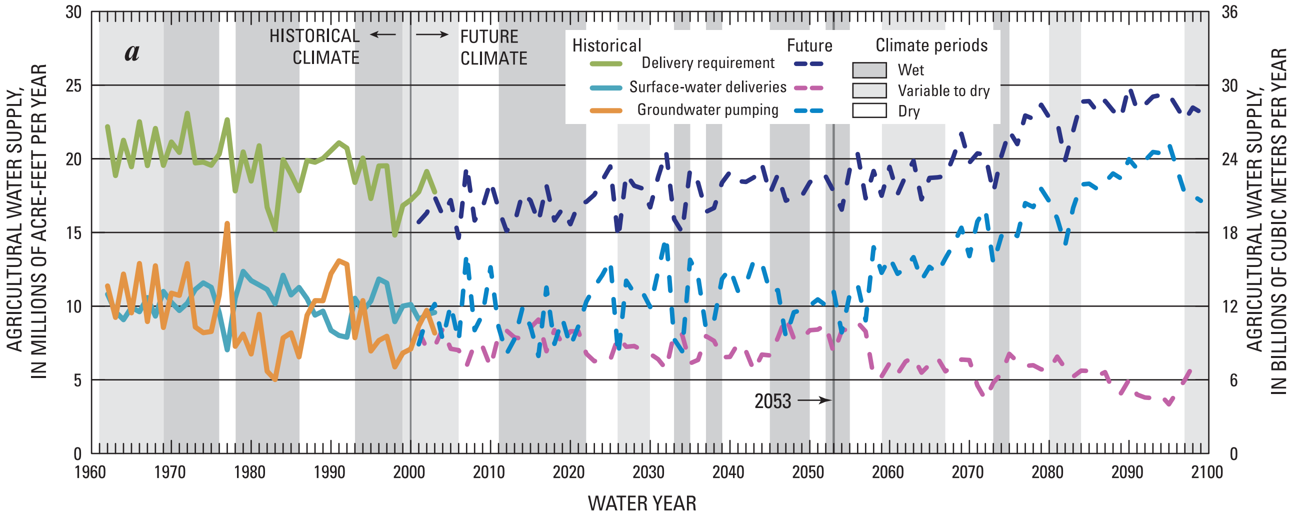

Figure 5. Graphs showing the hydrologic budgets with the GFDL-A2 scenario from CVHM for annual changes in (a) historical and future agricultural water supply and demand, (b) future changes in net streamflow infiltration, (c) future changes in groundwater storage, and (d) future changes in interbed storage, Central Valley, California.

regions on the western side of the San Joaquin Valley, some of the wells begin to approach the previous historical water level declines (well 14_28350) that would reinitiate additional land subsidence (Figure 6b). To the south in the Tulare basin where historical declines were greatest, the GFDL-A2 projection indicates the continuation of sustained water level declines of tens of meters (Figure 6c).

[43] Prior to the construction of the major canal delivery systems in the 1960s, storage depletion was a significant source of groundwater extractions, with about a third of the water supplied from fine-grained beds [*Ireland et al.*, 1984]. This storage depletion of water that came from fine-grained interbeds resulted in as much as 8.5 m (28 feet) of land subsidence [*Poland et al.*, 1975; *Ireland et al.*, 1984]. The historical simulation indicated as much as 3 m of additional simulated land subsidence during the more recent historical 42 year period (1961–2003) [*Faunt et al.*, 2009a, 2009b, 2009c, 2009d; *Hanson et al.*, 2010a] (Figure 7). The GFDL-A2 scenario yields additional extractions of water from interbed storage driven largely by pumpage during the dry conditions of the second half of the 21st century (Figure 5d). This loss of storage occurs largely in the Tulare Basin but is also present in the San Joaquin Basin and the northern regions that include the delta, eastside streams, and the Sacramento Valley.

[44] This integrated modeling method facilitates the analysis of the transition of conjunctive use that could result in new problems in unexpected regions. For example, much of the subsidence in this projection occurs adjacent to the Sierra Nevada where the transition from surface water- to groundwater-dominated irrigation is most extreme [*Hanson et al.*, 2010a]. The simulated future storage depletions are accompanied by renewed land subsidence in parts of the Tulare Basin (Figure 7) where federal, state, and local surface water canals traverse many of the areas projected to experience additional subsidence in the Sacramento, Delta subregion, San Joaquin, and Tulare basins. The integrated results help to indicate potential regions of land subsidence and, especially, differential subsidence that can threaten the integrity of these conveyances (Figure 7). Agricultural drainage and flood hazard zones, as well as transportation and urban infrastructure, might also be adversely affected by the transition of water supply to groundwater. If urban water demand increases at the 1.2% per year assumed here, storage depletion and land subsidence may also extend into urban areas. Thus, agricultural and urban demand driven by climate change and urban growth may collectively contribute to this secondary effect of groundwater storage depletion and limiting secondary effects.

[45] The supply and demand framework allows synthesis and analysis of basin-scale hydrologic budgets that can help water managers summarize the inflows and outflows of water across the landscape (Figure 8a) and in the groundwater flow system (Figure 8b). The time series of simulated landscape water budgets indicates reductions in precipitation, actual ET from groundwater uptake, and surface water deliveries, and an increase in groundwater pumpage (Figure 8a). Recharge and actual ET from water applied for irrigation remain relatively constant, and are largely supported by inefficient irrigation (Figure 8a). The groundwater budget shows the transition from recharge by deep percolation of precipitation to recharge from irrigation and from storage depletion that is caused by increased pumpage (Figure 8b). The projected increase in pumpage and resulting storage depletions, interbed storage losses, and increased leakage from streambeds during the sustained dry period of the late 21st century is driven by combinations of "business as usual" irrigation demands adjusting to the GFDL-A2 climate and increased water supply demands from urban growth (Figure 8b).

[46] The effects of climate change can also be assessed for specific subregions such as the delta. The analysis of increased urban growth combined with the small increase in sea level indicates that streamflow infiltration increases and groundwater outflow from the delta decreases under

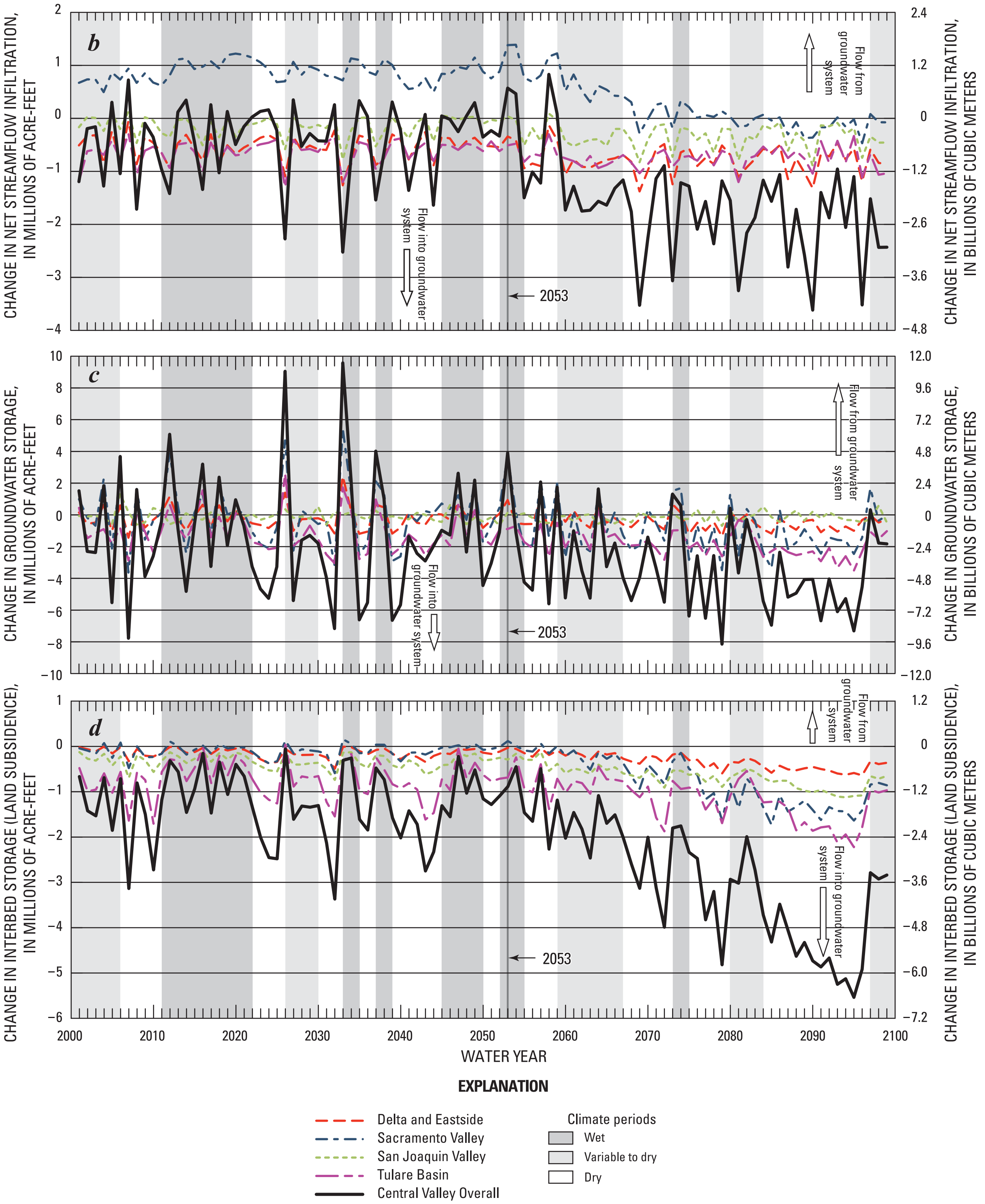

Figure 5. (continued)

the GFDL-A2 scenario. The increase in streamflow infiltration and storage depletion throughout the delta, and increased groundwater inflow at the delta's boundary over the century, underscore the potential effects of climate change from the GFDL-A2 scenario and urbanization on the hydrologic dynamics of the delta. These affects become greater with larger assumed percentages in growth of urban water demand, which underscores the potential combined effects of climate change on supply and demand as well as increased demand from additional urbanization.

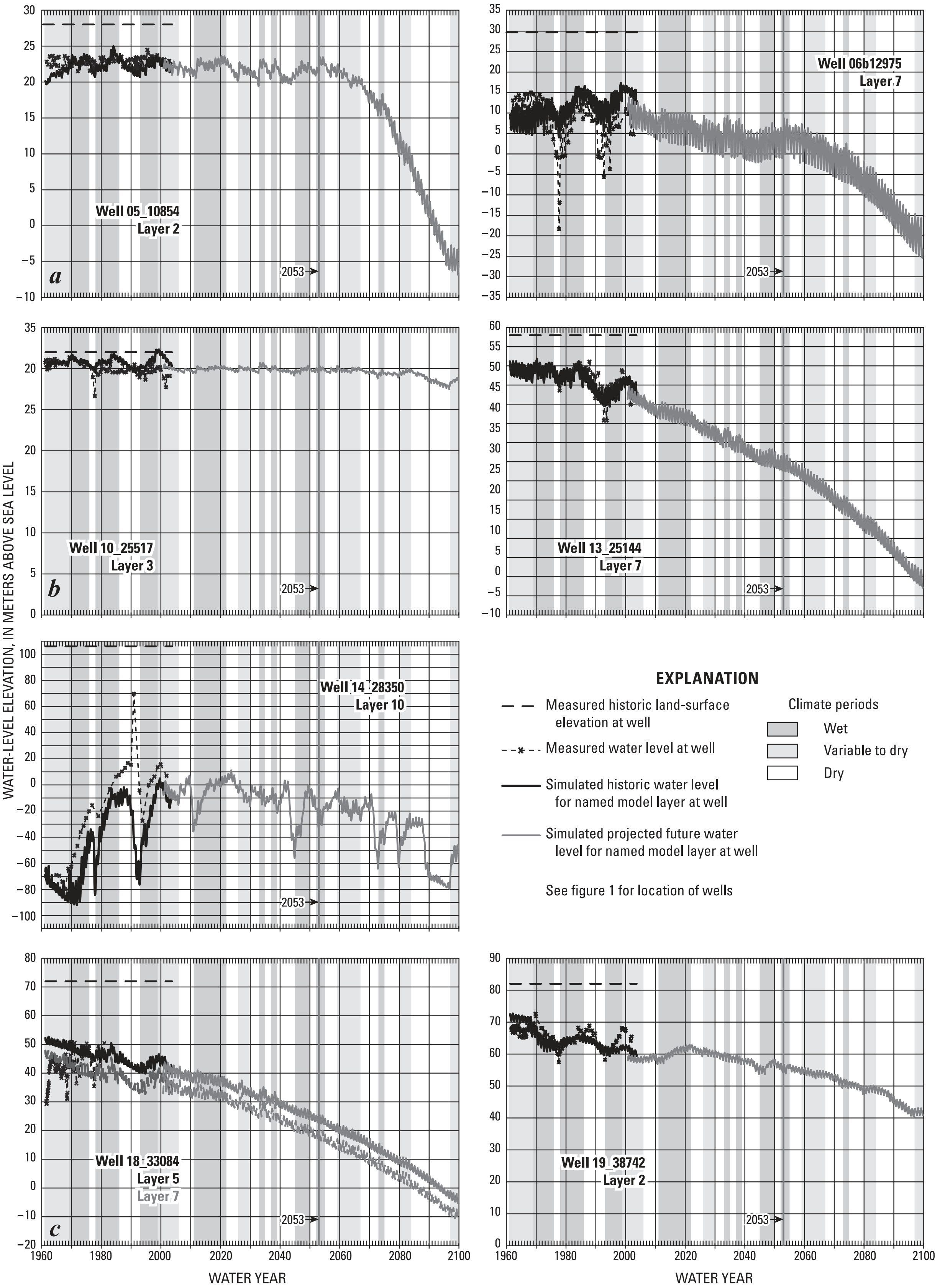

Figure 6. Graphs showing changes in groundwater levels for historical and future conditions with the GFDL-A2 scenario from CVHM for selected wells in (a) Sacramento Valley, (b) San Joaquin Valley, and (c) Tulare Basin, Central Valley, California.

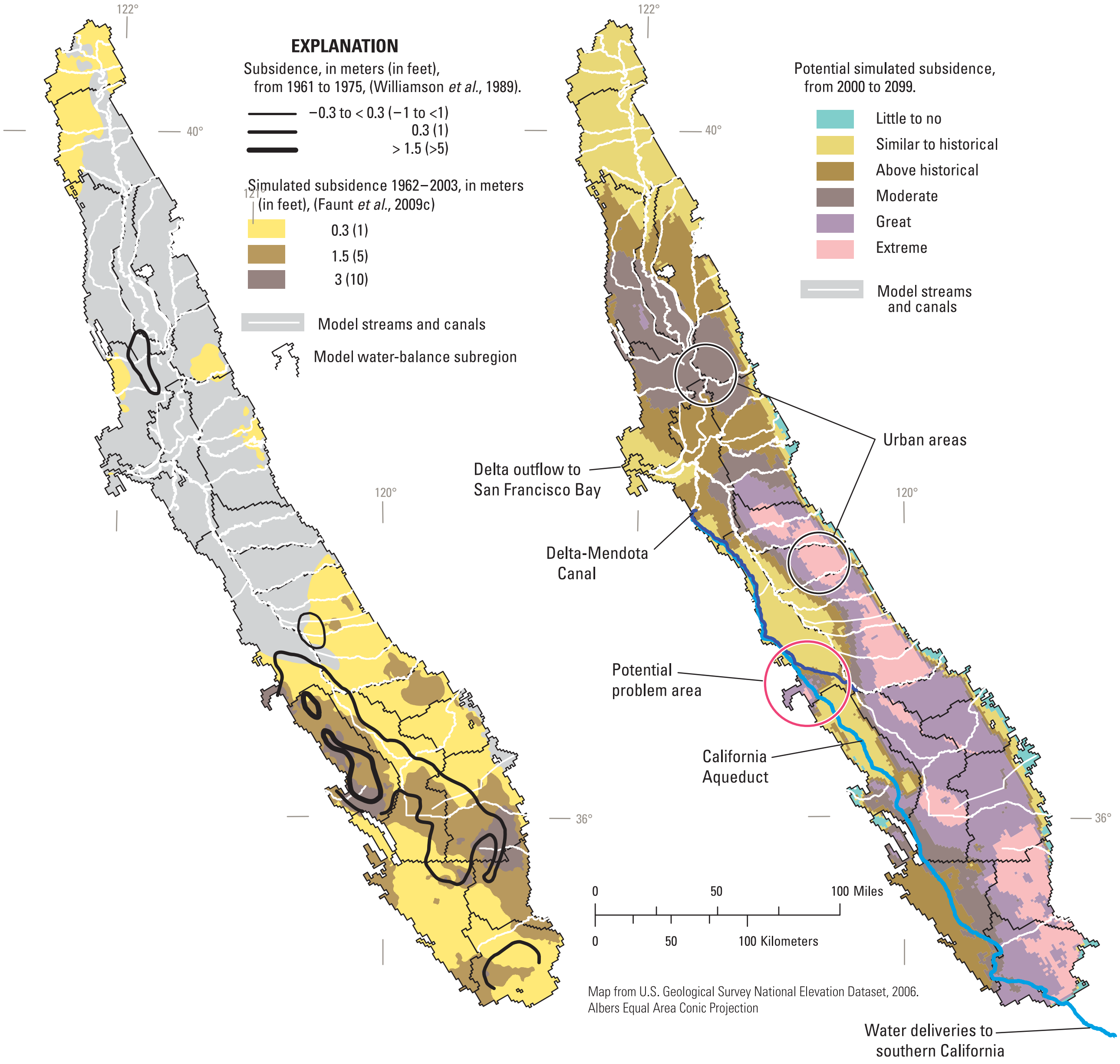

Figure 7. Map showing the historical land subsidence (1961–1975) and future land subsidence with the GFDL-A2 scenario and 1.2% urban growth from CVHM for the period 2000–2099, Central Valley, California. Modified from *Hanson et al.* [2010a].

4. Conclusions

[47] A method of linked physically based hydrologic models is demonstrated to provide a systematic analysis of direct and indirect effects of climate change on regional hydrologic systems. The feasibility of this supply and demand modeling framework method was illustrated here in the case of the California Central Valley and the adjacent Coast Ranges and Sierra Nevada where both climate change and climate variability affect conjunctive use and movements of water.

[48] While past extreme climate variability, such as pluvial periods and mega droughts, has affected the distribution of water in California, climate change due to greenhouse gas emissions will probably result in substantial temperature rises and could produce decreased precipitation, more sustained drought, and possibly an increased number of extreme events in the 21st century. Precipitation is the source of recharge and streamflow but in the Central Valley ET_p is greater than precipitation. In the application of the GFDL-A2 scenario, climate change results in diminished precipitation, decreased runoff from the surrounding mountains, warming-induced increases in ET_p, and consequently, increased pumpage and land subsidence in the Central Valley.

[49] This method simulates the transition from a predominantly surface water supply to groundwater supply because the models were designed to satisfy the need to incorporate the use and movement of water from the landscape, surface water and groundwater. In this scenario, the intermittent droughts in the first half of the 21st century are followed by severe persistent droughts in the second half of the 21st

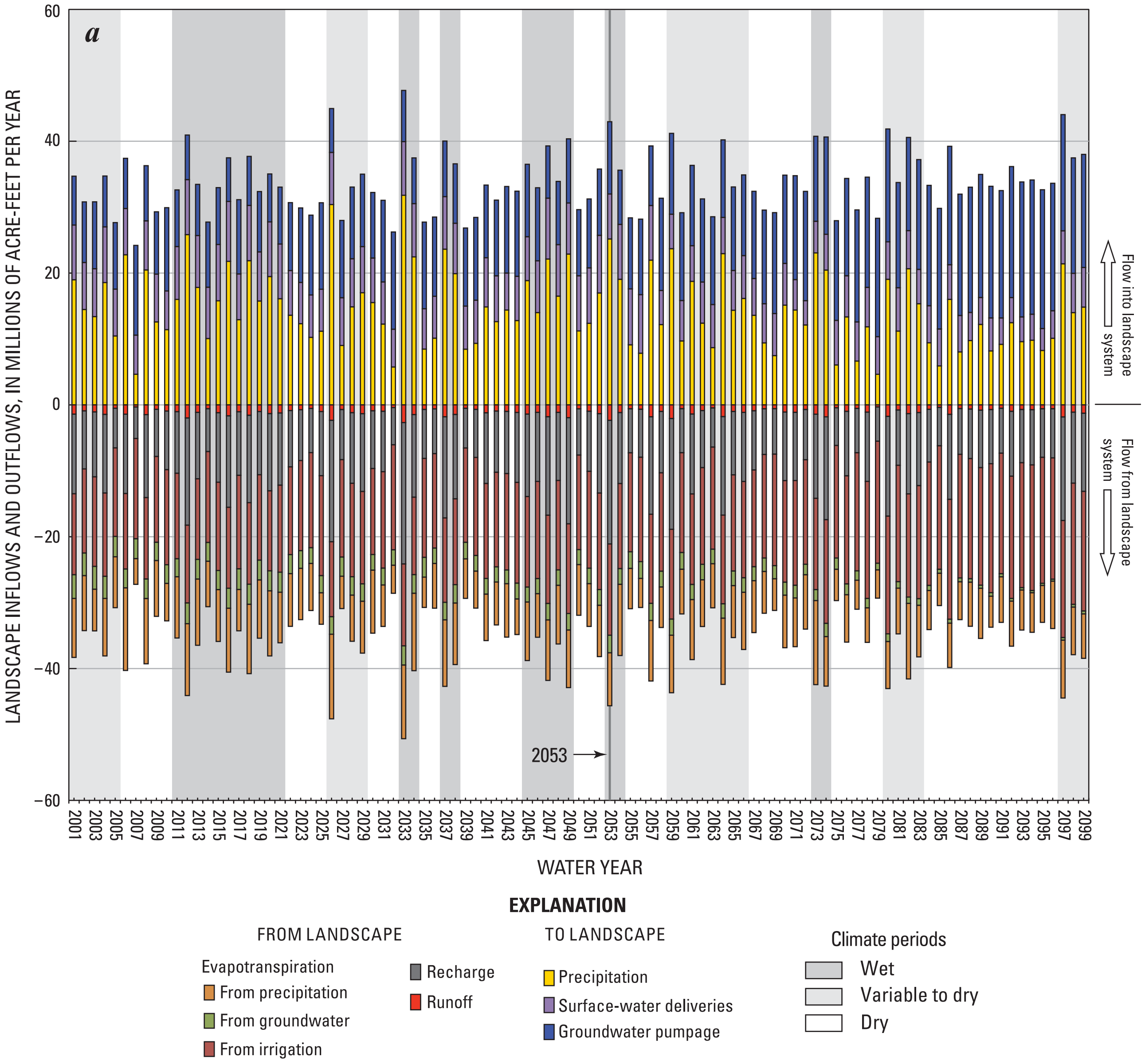

Figure 8. Graphs showing the future hydrologic budgets resulting from the use of the GFDL-A2 scenario in the CVHM of (a) the landscape and (b) the groundwater flow system, Central Valley, California.

century. However, because of the groundwater supply, these do not trigger a valley-wide operational drought (defined here as an interval when demand exceeds the engineered supplementary supplies so that the demands cannot be met by any available option). This analysis did not include adaptation by the agricultural sector, but even with this constraint, the existing engineered water supply and delivery systems may still be able to accommodate the projected changes. This ability to accommodate the projected changes is due, in large part, to the large number of wells that exist in the valley. Nonetheless the climatic droughts cause substantial effects on surface water and groundwater deliveries, and might trigger secondary effects such as increased land subsidence and differential land subsidence, reduced surface water deliveries and water for riparian habitat, and reductions in flows at the delta.

[50] The application of this modeling framework results in an example where these indirect effects of climate change and urban growth could become limiting factors for sustainability of the conjunctive use in the Central Valley. The combined future effects of climate change and urban growth have been assessed globally, and indicate an increased stress on water resources in California and other important watersheds elsewhere in the world [*Vorosmarty et al.*, 2010].

[51] In fact, the simulated reductions in outflow from the Sierra Nevada obtained from the GFDL-A2 scenario are accentuated farther downstream, where reduced flows from the delta reflect these reductions plus sustained irrigation demands and assumed, modest urban growth. Reductions in outflows from the mountains were greatest in the north and central parts of the Sierra Nevada and during the sustained droughts of the second half of the 21st century. The

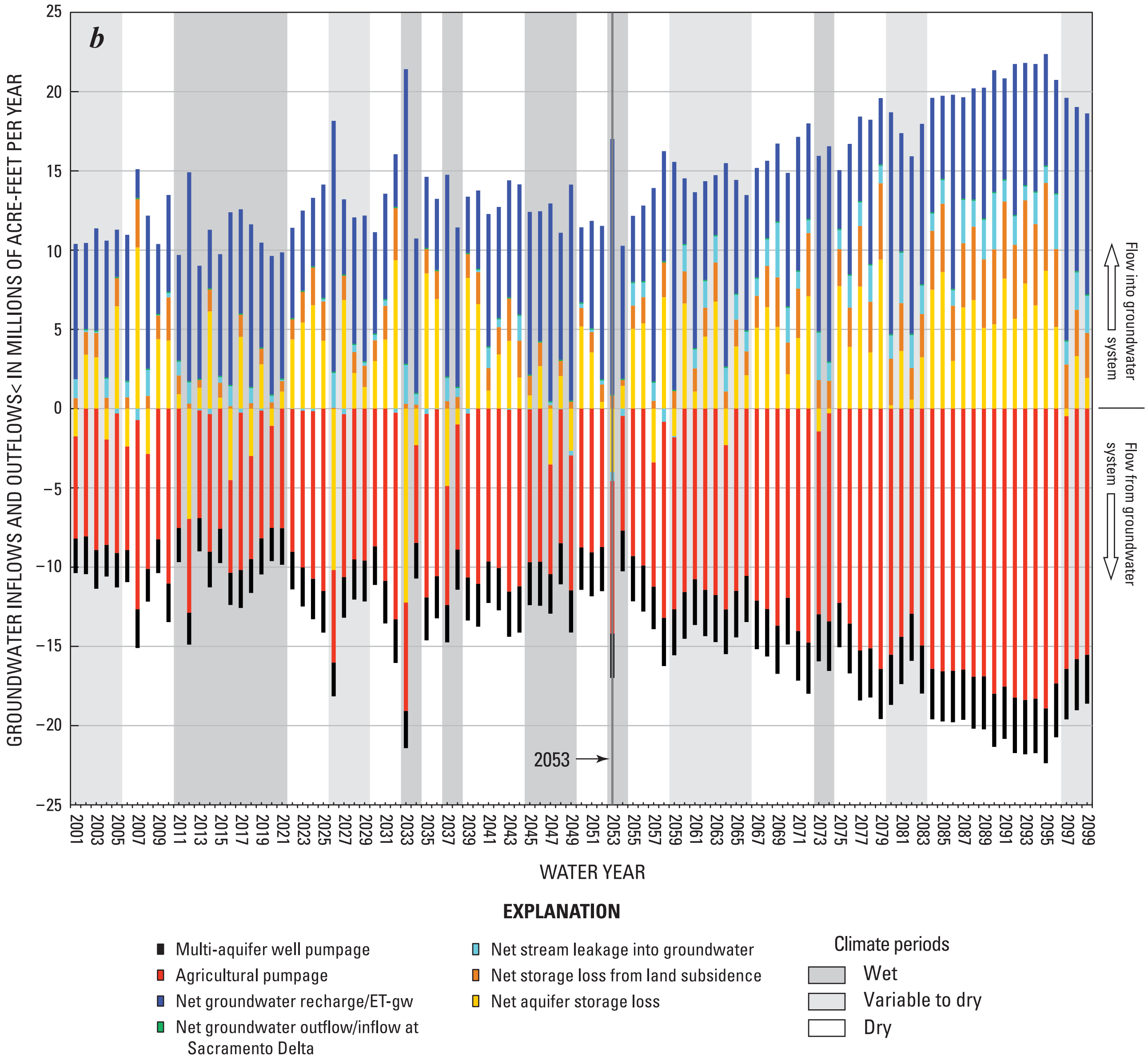

Figure 8. (continued)

reduced streamflows result in less surface water available for irrigation, urban water supply, and environmental uses. The changes in recharge, discharge, and groundwater storage in principal aquifers such as those of the Central Valley respond to climate change and the embedded climate variability that are greatest on the interdecadal scale. The effects from climate change are exacerbated by the modest urban growth imposed here, in agreement with *Vörösmarty et al.* [2000]. With land use held constant, the effects of the sustained droughts in the second half of 21st century are inseparable from the increasing natural and anthropogenic demands for water. Many other areas in the world may also be confronted by these combined effects.

[52] Increased demands for irrigation water to replace reductions in valley floor precipitation and plant uptake from groundwater is met, in the simulations, by increased groundwater pumpage. In turn, increased pumpage contributes to increased streamflow infiltration, reduced base flow, reduced groundwater outflows to the delta, increased depths to groundwater, and land subsidence. Meeting these demands ultimately results in the transition of conjunctive use from a surface water to a groundwater dominated system. This transition may cause additional land subsidence that could be hazardous to agriculture, transportation and urban infrastructure, and environmental habitat. Increased land subsidence is projected to occur where reductions in surface water supplies and related Sierra Nevada runoff are largest: in the Tulare Basin and along the southeastern San Joaquin and Sacramento Valleys. A long time may be required to recover from sustained groundwater storage depletion and captured surface water discharge [*Alley*, 2006].

[53] The linked models demonstrated here provide a supply and demand framework for hydrologic analysis of

streamflow, groundwater flow, pumpage, and related effects under a combination of climate change and urban growth that can be applied to other regional hydrologic systems. The simulation of a supply-constrained and demand-driven setting provides the basis for the analysis of conjunctive use and movement of water for human and natural components in the hydrosphere. Potential changes in groundwater storage, streamflow gains and losses, land subsidence, and consumption of water are linked in the modeling system to potential climate changes. Projections of the actual future climatic and hydrologic conditions are inherently uncertain, so it is not possible to provide accurate predictions. However, the present analysis of the Central Valley demonstrates that this method of linked models can provide an evaluation of potential points of vulnerability in the system and potential trends. In principle, with similar simulations of more climate and growth scenarios, the model system can also be used as part of a supply-constrained and demand-driven decision support system for planning and testing of adaptation strategies for part or all of a regional flow system such as the Central Valley. Because hydrologic predictions of actual future conditions are inherently uncertain and even nonunique for this particular model, this analysis provides trends and relative proportions of change in the hydrologic components on interannual to interdecadal periods of time from a climate change scenario that is not a forecast. Thus, only potential trends and relative proportions of the hydrologic budget predicted by the models may be considered reliable relative to the temporal scope and assumptions made within these projections of conjunctive use. This method can be applied in a wide variety of hydrologic settings and scales throughout the world's regional flow systems.

[54] The demand for water resources by people and agriculture also compete with environmental needs such as maintaining minimum streamflows, preventing seawater intrusions into and around the delta, and preserving habitats for fish and birds. Sustainable development is likely to require an integrated water management approach, and integrated resource modeling of the sort demonstrated here. The modeling approach used here has the potential to explore the long-term sustainability of system operations and conjunctive use through physical adaptation of the supply and demand components that could test alternate sources, uses, or policies. This could include the analysis of implementation of aquifer-storage-and recovery operations, imposing groundwater allotments to limit overexploitation of groundwater in selected regions, or drought deficiency optimization such as acreage optimization or water stacking. This approach can also facilitate physically based and physically constrained economic, environmental, or policy adaptation through linkages to other types of models. A suite of linked physically based, supply and demand framework models as is demonstrated here is likely to become a necessary tool for developing elements of a decision support system for evaluating the sustainability of conjunctive use within regional hydrologic systems.

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