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DROUGHT RESILIENCE OF THE CALIFORNIA CENTRAL VALLEY SURFACE-GROUND-WATER-CONVEYANCE SYSTEM[1]

Norman L. Miller, Larry L. Dale, Charles F. Brush, Sebastian D. Vicuna, Tariq N. Kadir, Emin C. Dogrul, and Francis I. Chung[2]

ABSTRACT: A series of drought simulations were performed for the California Central Valley using computer applications developed by the California Department of Water Resources and historical datasets representing a range of droughts from mild to severe for time periods lasting up to 60 years. Land use, agricultural cropping patterns, and water demand were held fixed at the 2003 level and water supply was decreased by amounts ranging between 25 and 50%, representing light to severe drought types. Impacts were examined for four hydrologic subbasins, the Sacramento Basin, the San Joaquin Basin, the Tulare Basin, and the Eastside Drainage. Results suggest the greatest impacts are in the San Joaquin and Tulare Basins, regions that are heavily irrigated and are presently overdrafted in most years. Regional surface water diversions decrease by as much as 70%. Stream-to-aquifer flows and aquifer storage declines were proportional to drought severity. Most significant was the decline in ground water head for the severe drought cases, where results suggest that under these scenarios the water table is unlikely to recover within the 30-year model-simulated future. However, the overall response to such droughts is not as severe as anticipated and the Sacramento Basin may act as ground-water insurance to sustain California during extended dry periods.

(KEY TERMS: drought simulation; surface-ground-water response; pumping.)

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INTRODUCTION

The western United States (U.S.) has experienced periods of long drought conditions since the last glacial epoch 11,000 years ago. The period between 900 and 1400 A.D. was a time when severe long-duration droughts occurred in the western U.S. (Cook *et al.*, 2004). This medieval mega-drought period was followed by a less severe drought period that was

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[2]Respectively, Staff Scientist and Adjunct Professor (Miller), Climate Science Department, Berkeley National Laboratory and Geography Department, University of California, Berkeley, California 90-1116, One Cyclotron Road, Berkeley, California 94720; Staff Scientist (Dale), Energy Analysis Department, Berkeley National Laboratory, Berkeley, California 90-4000, One Cyclotron Road, Berkeley, California; Water Resources Engineer, Senior Engineer, Water Resources Engineer, Principal Engineer, (Brush, Kadir, Dogrul, Chung), Modeling Support Branch, Bay-Delta Office, Department of Water Resources, 1416 9th Street, P.O. Box 942836, Sacramento, California 94236; and Graduate Student (Vicuna), Civil and Environmental Engineering Department, University of California, Berkeley, Davis Hall, Berkeley, California 94720 (E-Mail/Miller: nlmiller@lbl.gov).

coincident with the Little Ice Age cooling period. Samples from sediments, tree rings, and tree stumps, combined with isotope dating analysis have been used to reconstruct these naturally occurring droughts that lasted 50 to more than 100 years (Stine, 1994; Herweijer *et al.*, 2006; Cook *et al.*, 2007). Indeed, two epic drought periods, one lasting from approximately 900-1100, and the second lasting from about 1200-1350, contributed to the decline and disappearance of the Anasazi people, a culture that relied on irrigated agriculture to support its population. Drought is also seen as a contributing factor in the failure of European colonies in South Carolina and North Carolina in the 1500s. More recently, four droughts in the western U.S. centered on AD 1710, 1770, 1850, and 1930 have been associated with the Pacific Decadal Oscillation (PDO), and indicate drought recurrence intervals of 60-80 years (Benson *et al.*, 2003) and a linkage to large-scale climatic phenomena.

During the last 150 years, California has been in a slightly above average wet regime, with an annual average precipitation of 58 cm (23 inches), and at least 11 significant drought periods (Ingram *et al.*, 1996; Cook *et al.*, 2004). At the same time, California Central Valley agriculture has expanded over most of the Valley floor, and includes a system of managed irrigation and water conveyance that has assumed climatically stationary conditions for conveyance system development and planning. The 1929-1934 drought has traditionally been the benchmark event used for designing storage capacity and yield of large California reservoirs. The stationarity principle may no longer be valid, as substantial anthropogenic changes in Earth's climate are altering the means and extremes of precipitation, evapotranspiration, and rates of discharge to rivers (Milly *et al.*, 2008). Changes in the temperature regime in California associated with projected future climate are expected to result in reduced winter snowpack and increased winter runoff (Miller *et al.*, 1999; Hayhoe *et al.*, 2004; Maurer and Duffy, 2005). In addition, the population of California's Central Valley has increased from less than 3 million people in 1970 to more than 6 million in 2002, and is projected to increase to 15 million people by 2050 (U.S. Bureau of the Census 1982; California Department of Finance 2007). Since the 1970s, as the urban area of the Central Valley has increased, agricultural acreage has remained relatively constant by expanding into previously uncultivated land. The increase in population coupled with constant agricultural acreage has resulted in steadily increasing water demands. Approximately 35% of the water demand in the Central Valley is currently met with ground water (California Department of Water Resources 2003), with pumping rates increasing in years of reduced surface water availability. Flow deficits associated with future climate scenarios, coupled with present and future levels of water demand, may inflict significant stress on Central Valley aquifers. In light of these challenges, the California Department of Water Resources (CDWR) and other water agencies have begun to evaluate new approaches for incorporating the changing climate into water resources planning and management (CDWR, 2006; Anderson *et al.*, 2008).

The goals of this study are to quantify the impacts of long-term hydrologic droughts – a first-order approximation of an analogue for climate change related snowpack reduction – on water storage, and to illustrate the potential for surface and subsurface storage to limit the adverse impacts of drought and snowpack reduction on water supply and hydropower generation. This includes how ground-water pumping compensates for reductions in surface water inflow; the extent to which the water table is reduced; and how, when, and if this system recovers or reaches a new equilibrium. In the next section, we provide details on our approach for simulating persistent droughts in the California Central Valley. This is followed by the results and discussion section, then our summary and conclusions.

APPROACH

This analysis of the impacts of sustained droughts in the California Central Valley is based on a series of specified reductions in net surface water inflows observed during the 1923-1972 period. The reductions considered in the study represent a 30% (below average), 50% (dry), and 70% (critically dry) effective reduction for periods ranging from 10 to 60 years, and were applied to the CDWR's California Central Valley Ground water-Surface Water Simulation Model (*C2VSIM*). The methodology used here is part of a series of analyses that allow for the decomposition and response term by term, allowing for a reductionist evaluation of the impacts of decreases in net surface flow from reservoirs and Central Valley precipitation. Previous studies of California's future water supply were based on downscaled climate model projections with hydrologic model simulations and permutations of the 1922-1993 unimpaired streamflows (Miller *et al.*, 2003) with an operating criterion of maximizing statewide water supply net benefits (e.g., Lund *et al.*, 2003; Zhu *et al.*, 2005; Tanaka *et al.*, 2006; Medellin-Azuara *et al.*, 2008). However, these studies are unable to pin down the term-by-term isolated response to droughts, present day or future. With that in mind, it was deemed essential to keep land use unchanged in this phase of analysis in order to understand only the response to reduced flows under current conditions.

The CDWR is addressing global climate change in the California Water Plan, Bulletin 160 (CDWR, 2005a). Specified drought scenarios act as an analogue to projected reductions in snowpack-derived surface water flows. Rather than focus on causes of global climate change, which are being addressed by other agencies and research institutions, the CDWR Water Plan looks at potential impacts of climate change on water resources in California and strategies for adapting to these changes.

Model Descriptions

Two computer applications developed by CDWR, the surface water allocation model California Simulation Model (*CALSIM II*) and the integrated hydrologic model California Central Valley Groundwater-Surface Water Simulation Model (*C2VSIM*), were used for this study.

CALSIM II. The *CALSIM* model (Draper *et al.*, 2004) is a general-purpose, network flow, reservoir and river basin water resources allocation model developed jointly by CDWR and the U.S. Bureau of Reclamation. It is used for evaluating operational alternatives of large, complex river basins. *CALSIM* integrates a simulation language for flexible operational criteria specification, a mixed integer linear programming solver for efficient water allocation decisions, and graphics capabilities for ease of use. A linear objective function describes the priority in which water is routed through the system and the constraints set the physical and operational limitations toward meeting the objective. *CALSIM* maximizes the objective function in each time period to obtain an optimal solution that satisfies all constraints.

CALSIM was originally designed, and has been successfully implemented as a planning model of the State Water Project (SWP) and Central Valley Project (CVP) system to examine the range of options to improve supply reliability. The second-generation version used here (*CALSIM II*) calculates the reservoir operations and time dependent rim-flow into the Central Valley on monthly time steps, providing the needed boundary conditions to *C2VSIM*.

C2VSIM. The *C2VSIM* model (Brush *et al.*, 2008) was developed as an application of the CDWR's Integrated Water Flow Model (IWFM; CDWR, 2005b,c, 2006). IWFM simulates land-surface processes, surface water flow and ground-water flow. The land-surface module computes infiltration and runoff from net precipitation; consumptive use by native vegetation, irrigated crops and urban areas; surface water diversion and application; ground-water pumping and application; infiltration and return flow from irrigation; and recharge. Surface water flow is simulated as a function of flow from upstream reaches, tributaries and lakes; surface runoff; agricultural and urban return flows; diversions and bypasses; and exchanges with the ground-water flow system. Horizontal and vertical ground-water flow are simulated using the Galerkin finite-element method and a quasi-three-dimensional approach utilizing the depth-integrated ground-water flow equation for horizontal flows in each aquifer layer and leakage terms for vertical flow between aquifer layers. To the extent that is practical, IWFM directly incorporates readily available historical and spatial datasets, including precipitation, the Natural Resource Conservation Service (NRCS) runoff curve number, surface water inflows and diversions, land use and crop acreages.

The *C2VSIM* model simulates land-surface processes, ground-water flow and surface water flow in the alluvial portion of the Central Valley (Figure 1) using a monthly time step. *C2VSIM* covers an area of 51,394 km^2 (19,834 mi^2), and incorporates 1,392 nodes forming 1,393 elements and 3 layers, 431 stream nodes delineating 74 stream reaches with 97 surface water diversion points, 2 lakes, and 8 bypass canals (Figure 1A). Surface water inflows are specified for 35 gaged streams and simulated for ungaged small watersheds. The model area is divided into 21 subregions (Figure 1B), and ground water and surface water are allocated to meet monthly water demands in the land-surface process within each subregion.

Regional-scale parameter values were calibrated using the PEST parameter estimation program (Doherty, 2005) for the 25-year period 1975-1999, using ground-water head observations at 221 wells, paired ground-water head observations for calculating vertical head gradients at nine locations, monthly river flow observations at seven locations, and stream-aquifer interaction values at 65 locations along 33 river reaches. The preliminary calibration produced hydraulic parameter values that reflect the geologic composition of subregions within the Central Valley. The average difference between simulated and observed ground-water heads for water years 1975-1999 was 4.43 m (13.5 ft), the RMSE was 24.1 m (73.4 ft), and the RMSE/range was 11%. The ground-water heads produced by the model are considered reasonably accurate given the discretization of the finite element grid, in which the average spacing between model nodes is on the order of 8 km (5 miles), and the areal extent of the water budget subregions. Simulated and observed stream to

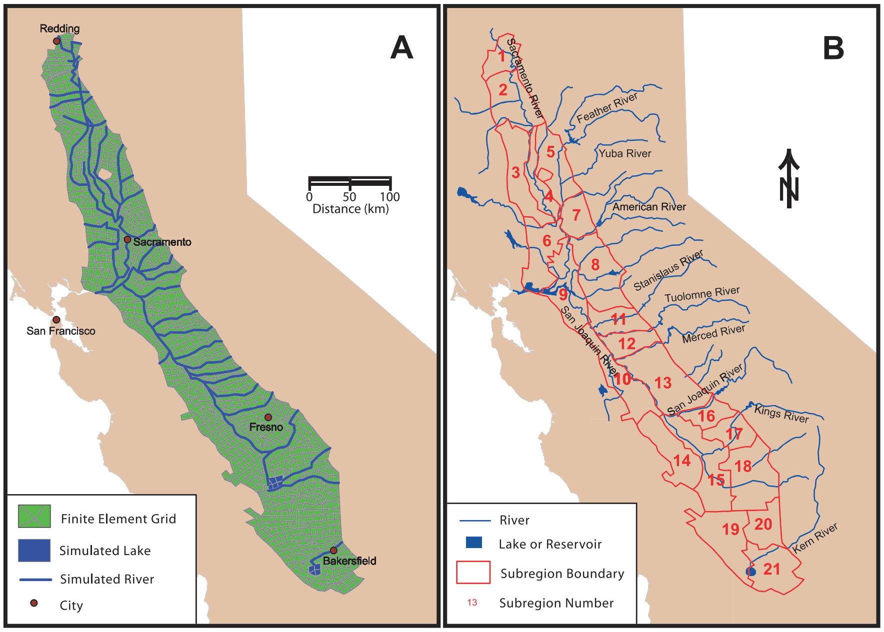

FIGURE 1. *C2VSIM* Domain: (A) Finite Element Grid and (B) Water Budget Subregions.

ground-water flows are of the same order of magnitude and in the same direction for a majority of the simulated river reaches. The average difference between simulated and observed surface water flows for the Sacramento Valley and the San Joaquin Basin for 1975-1999 was 0.044 km^3/mn [35.7 thousand acre-feet per month (taf/mn)], the RMSE was 0.17 km^3/mn (139 taf/mn), and the RMSE/range was 2%. Given that an average of 2.6 km^3/mn [2.1 million acre-feet per month (maf/mn)] flows through these basins, the surface water flow system representation in the calibrated model is considered to be very accurate.

Drought Scenarios

Drought scenarios used here are constructed surface water flow reductions representing scenarios with mean reductions in precipitation ranging from 30 to 70% for periods ranging from 10 years to 60 years, with a 10-year spin-up and a 30-year recovery. The *C2VSIM* boundary forcing was generated using the *CALSIM II* model and historical flow observations of Central Valley rim flows based on the specified reductions corresponding to each scenario. The notation for the set of 12 scenarios is given in Table 1.

The methodology used to create hypothetical drought scenarios consisted in selecting randomly hydrologic dry years (in terms of reservoir inflow) from the historic record and appending them together to create the specified droughts. For each one of these time series of appended years we extracted time series of reservoir releases and surface water deliveries resulting from an historic simulation done with the *CALSIM II* model. These time series were matched to the required *C2VSIM* input needs. It wasn't assured through this method that the exact specified amount in reduction in deliveries would occur, because there is not a perfect correlation between inflows to reservoirs and deliveries, and also because the reductions were assumed to be homogeneous throughout the different regions included in the model. An analysis of the input data that went into the model shows that the derived scenarios were underestimations of the expected reductions and the distribution of reductions were not homogeneous.

The remainder of this study refers to the three drought intensity levels as light (30%), moderate (50%), and severe (70%), noting that the reductions in deliveries are lower than the reductions in reservoir inflows. The specified drought scenarios and reductions in precipitation, reservoir releases, and surface water deliveries are presented in Table 2.

RESULTS AND DISCUSSION

The Central Valley region covers 51,394 km^2 [12.7 million acres (Mac)], with a cropped area of 27,518 km^2 (6.8 Mac) in 2003. The Central Valley can be divided into five hydrologic regions: the Sacramento Valley covers the northern part of the Central

TABLE 1. Drought Scenario Notation.

Specified Scenarios	10 Years	20 Years	30 Years	60 Years
30% reduction	30_10	30_20	30_30	30_60
50% reduction	50_10	50_20	50_30	50_60
70% reduction	70_10	70_20	70_30	70_60

TABLE 2. Drought Scenario Reductions in Precipitation, Releases, and Deliveries.

	Percentage Reduction in:		
Scenario	Precipitation (%)	Releases (%)	Deliveries (%)
30_10	26	40	26
30_60	25	41	27
50_10	34	50	41
50_60	27	54	46
70_10	39	61	53
70_60	39	59	51

Valley (model subregions 1-7; 14,927 km^2), the San Joaquin Basin is in the center of the Central Valley (model subregions 10-13; 9,950 km^2), the Tulare Basin in the southern end of the Central Valley (subregions 14-21; 19,958 km^2), the Sacramento-San Joaquin Delta (subregion 9; 2,936 km^2), and the Eastside Streams to the east of the Sacramento-San Joaquin Delta (subregion 8; 3,624 km^2). The impacts of the simulated droughts are discussed for the Central Valley, and for the Sacramento Basin, Eastside Drainage, San Joaquin Basin, and Tulare Basin, with a detailed focus on three drought scenarios, the 30-year moderate drought, the 60-year slight drought, and the 60-year severe drought. Simulated river flows in the Sacramento-San Joaquin Delta region are dominated by surface water transfers, and drought impacts on this region were therefore omitted from this study. To compare impacts across the four hydrologic regions, all flow rates were normalized against the region area, transforming volume per area to depth; normalizing flow rates against crop area would yield similar results as normalizing against regional area, as the regional water budgets are dominated by agricultural water use.

In response to drought-induced reductions in surface water availability, combined with static demands based on a fixed land use and population, the IWFM application automatically increases ground-water pumping to exactly meet the specified agricultural and urban water demands. The reduced surface water flows and precipitation and increased ground-water pumping induce changes in water table altitude, ground-water volumetric storage, and stream to ground-water flow. Ground-water recharge is also reduced owing to both reduced precipitation at the land surface and reduced recoverable losses (i.e., canal leakage) from surface water diversions. The 30-year recovery period and fixed land use and demands were required to isolate the impacts associated with surface water flow reductions alone. Future studies planned as part of this work include sequential and combined changes in both the land use types and demands.

Surface Water Diversions

The 12 simulated droughts all begin with the same initial conditions, and spin-up for 10 years, during which surface diversions across the Central Valley average 13.4 km^3/year (10.9 maf/year). Reservoir releases and surface water diversions were simulated by *CALSIM II* in response to specified reservoir inflows and constant 2003-level demands for each of the three levels of drought. Surface water diversions were lower than base period diversions in all months (Table 3), except for December diversions under the slight drought scenario, which were elevated due to the shift of the runoff hydrograph to increased winter runoff. After the 10-year spin-up period, surface water diversions in the Central Valley fall 39% during the severe drought scenario, 22% during the moderate drought scenario, and 13% during the slight drought scenario (Table 4). Each scenario concludes with a 30-year recovery period.

It is apparent from the simulation results that drought scenario impacts are concentrated in the San Joaquin and Tulare Basins (Figure 2). In the severe 60-year drought scenario, these basins experience average annual declines of 0.15 and 0.13 m (0.46 and 0.41 ft), respectively, in surface deliveries compared with the base period (Table 5), representing a 43% decline in the San Joaquin Basin and a 70% decline in the Tulare Basin. The Sacramento Basin and Eastside Drainage experience declines of 27 and 60%, respectively. In the moderate 30-year drought, the Sacramento Basin, Eastside Drainage, San Joaquin Basin, and Tulare Basin experience declines of 5, 40, 19, and 62% respectively. In the light 60-year drought scenario, average annual surface water deliveries increase by 7% in the Sacramento Basin (due to higher winter flows), and decline by 43, 17 and 46% for the Eastside Drainage, San Joaquin Basin, and Tulare Basin, respectively.

Ground-Water Pumping

Farmers in the Central Valley have historically increased ground-water pumping during drought

TABLE 3. Monthly Change in Surface Water Diversions Compared With Base Period Diversions.

Month	Severe Drought (m/year) (%)	Moderate Drought (m/year) (%)	Slight Drought (m/year) (%)
Oct	65	68	88
Nov	73	73	99
Dec	93	86	118
Jan	32	46	65
Feb	15	19	23
Mar	18	25	30
Apr	65	75	89
May	49	70	81
Jun	61	76	90
Jul	63	81	94
Aug	59	74	86
Sep	50	67	79
Annual	49	61	74

TABLE 4. Impact of Simulated Droughts on Surface Water Diversions.

Hydrologic Region	Base Period (km^3/year)	Severe Drought (km^3/year)	Moderate Drought (km^3/year)	Slight Drought (km^3/year)
Sacramento	4.73	3.44	4.48	5.06
Eastside	0.02	0.01	0.01	0.01
San Joaquin	3.24	1.79	2.62	2.69
Tulare	3.57	1.07	1.37	1.93
Central Valley	13.44	8.20	10.46	11.75
Change (%)		39%	22%	13%

periods to make up for declines in surface water deliveries. To maintain constant irrigation levels in the entire Central Valley during the simulated droughts, ground-water pumping increased by 71% in the severe drought, 49% in the moderate drought, and 27% in the slight drought scenario (Table 6). Interestingly, drought period ground-water pumping is greater than the reduction in surface water diversions. For example, Central Valley ground-water pumping increases 0.12 m/year (0.36 ft/year) in the severe drought, when surface water diversions declined only 0.11 m/year (0.33 ft/year). Increases in ground-water pumping in the San Joaquin Basin and Tulare Basin range from 0.01 to 0.04 m/year (0.04 to 0.12 ft/year) greater than the reduction in surface water diversions. This increase in ground-water pumping is required to compensate for the reduced precipitation experienced during drought years (Table 2). Indeed, changes in ground-water pumping may be a better indicator of drought severity than changes in surface water diversions in most regions. For example, ground-water pumping in the Eastside Drainage increases by 0.05 m/year (0.16 ft/year) in the severe drought scenario, 0.04 m/year (0.13 ft/year) in the moderate drought scenario, and 0.02 m/year (0.07 ft/year) in the slight drought scenario, while surface water diversions in this region remain close to base period levels (Table 6).

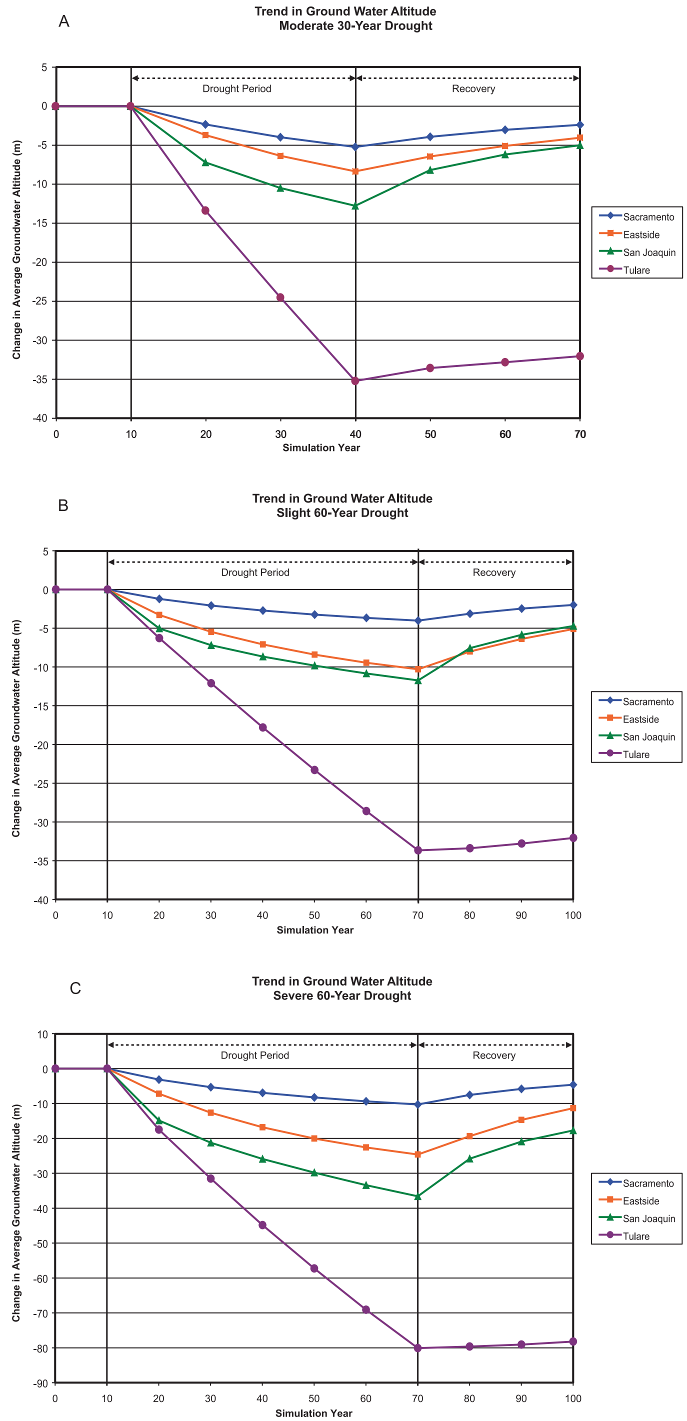

FIGURE 2. Ground-Water Trends Before, During and After (A) a Moderate 30-Year Drought, (B) a Slight 60-Year Drought, and (C) a Severe 60-Year Drought.

TABLE 5. Surface Water Diversions in Base and Drought Periods.

Hydrologic Region	Base Periofd (m/year)	Change From Base Period Severe Drought (m/year)	Moderate Drought (m/year)	Slight Drought (m/year)
Sacramento	0.34	−0.09	−0.02	0.02
Eastside	0.005	−0.003	−0.002	−0.002
San Joaquin	0.35	−0.15	−0.07	−0.06
Tulare	0.19	−0.13	−0.12	−0.09
Central Valley	0.28	−0.11	−0.06	−0.03
Change (%)		−38%	−22%	−12%

TABLE 6. Impact of Drought on Ground-Water Pumping.

Hydrologic Region	Base Period (m/year)	Change From Base Period Severe Drought (m/year)	Moderate Drought (m/year)	Slight Drought (m/year)
Sacramento	0.06	0.04	0.02	0.00
Eastside	0.15	0.05	0.04	0.02
San Joaquin	0.13	0.17	0.10	0.07
Tulare	0.29	0.17	0.14	0.07
Central Valley	0.16	0.12	0.08	0.04
Change (%)		71%	49%	27%

Aquifer Recharge

In a normal year, the Central Valley aquifers are recharged with excess from surface irrigation deliveries and rainwater percolation. For the Central Valley as a whole, this aquifer recharge generally exceeds ground-water withdrawals, although withdrawals exceed recharge in local areas of persistent ground-water overdraft (CDWR, 2003). In the base period, for example, the Central Valley ground-water recharge is 0.21 m/year (0.63 ft/year) (Table 7) compared to ground-water pumping of 0.16 m/year (0.50 ft/year) (Table 6). Excess ground-water storage derived from recharge in normal years helps to maintain ground-water storage levels during short-duration droughts when there is a dramatic decline in recharge. Average recharge across the Central Valley drops 14%, during the slight drought scenario, to as much as 42%, during the severe drought scenario (Table 7).

TABLE 7. Impact of Drought on Aquifer Recharge.

Hydrologic Region	Base Period (m/year)	Change From Base Period Severe Drought (m/year)	Moderate Drought (m/year)	Slight Drought (m/year)
Sacramento	0.21	−0.13	−0.08	−0.05
Eastside	0.05	−0.03	−0.03	−0.01
San Joaquin	0.24	−0.11	−0.06	−0.03
Tulare	0.21	−0.07	−0.06	−0.02
Central Valley	0.21	−0.09	−0.06	−0.03
Change (%)		−42%	−28%	−4%

Annual rainfall rates are highest in the northern Sacramento Basin and lowest in the southern Tulare Basin. Under the simulated drought scenarios, recharge varies across regions in proportion to changes in both surface water deliveries and rainfall. In the severe drought scenario for example, the Sacramento, San Joaquin, and Tulare Basins experience large declines in both precipitation and surface water deliveries and register large declines in aquifer recharge. The regional variation in rainfall helps to explain the regional variation in recharge not explained by regional differences in surface water deliveries.

Stream-Aquifer Flows

In normal years, the rivers in the Sacramento and San Joaquin Basins are net "gaining rivers," meaning that their flow is increased by a net movement of water from aquifers that are adjacent to rivers (Table 8). Alternatively, in normal years, the rivers in the Eastside Drainage and Tulare Basin are "losing rivers," with a net movement of water out of rivers and into adjacent aquifers. Stream-aquifer flows in the Sacramento and San Joaquin Basins are larger than those in the Eastside Drainage and Tulare Basin, and tend to dominate the average stream-aquifer flow in the Central Valley, which experiences a net flow of water from aquifers to rivers in normal years. The net flow of water from ground water to rivers decreases during droughts as regional ground-water levels decline in response to reduced recharge and increased withdrawals. In addition, flows from rivers to aquifers decrease because there is less water available in the rivers. Net ground-water discharges

TABLE 8. Impact of Drought on Stream-Aquifer Flows.

Hydrologic Region	Base Period (m/year)	Severe Drought (m/year)	Moderate Drought (m/year)	Slight Drought (m/year)
Sacramento	−0.131	−0.036	−0.084	−0.104
Eastside	0.037	0.018	0.018	0.023
San Joaquin	−0.076	0.006	−0.036	−0.040
Tulare	0.015	0.011	0.013	0.016
Central Valley	−0.078	−0.036	−0.058	−0.064
Change (%)		−68%	−32%	−23%

Note: Positive values are from the stream to the aquifer, and negative values are from the aquifer to the stream.

to rivers decline 23% in a slight drought, 32% in a moderate drought, and 68% in a severe drought (Table 8). The reduction in ground-water discharge to rivers limits the decline of ground-water levels during droughts, and also contributes to streamflow reduction beyond the reduction in valley-rim inflow.

Changes in Aquifer Storage

The change in aquifer storage over time is the sum of aquifer withdrawals, including ground-water pumping and discharges to streams, minus the aquifer inflows, including stream inflows and irrigation recharge. Changes in boundary flows have an additional, but very minor, impact on storage levels. During the base period (a mix of normal and above normal rainfall years), Central Valley storage increases by 0.03 m/year (0.10 ft/year). During the drought scenarios, Central Valley aquifer storage declines by 0.08 m/year (0.26 ft/year) in the slight drought scenario to 0.19 m/year (0.57 ft/year) in the severe drought scenario (Table 9).

Ground-Water Levels

Central Valley ground-water levels adjust to changes in storage, rising during the base period and falling during the drought scenarios. During the base period, average Central Valley ground-water levels rise 0.09 m/year (0.29 ft/year), with average levels in the Sacramento and San Joaquin Basins increasing by 0.08 m/year (0.24 ft/year) and 0.22 m/year (0.66 ft/year), respectively, and the Tulare Basin increasing by only 0.02 m/year (0.07 ft/year). Average Central Valley ground-water levels decline 0.29 m/year (0.88 ft/year) under the slight drought scenario and 0.77 m/year (2.33 ft/year), respectively, during the light and severe drought scenarios, with substantial variation shown by region (Table 10).

TABLE 9. Impact of Drought on Aquifer Storage.

		Change From Base Period		
Hydrologic Region	**Base Period (m/year)**	**Severe Drought (m/year)**	**Moderate Drought (m/year)**	**Slight Drought (m/year)**
Sacramento	0.069	−0.12	−0.10	−0.073
Eastside	0.027	−0.12	−0.10	−0.078
San Joaquin	0.057	−0.23	−0.15	−0.096
Tulare	−0.007	−0.25	−0.20	−0.095
Central Valley	0.034	−0.19	−0.14	−0.084

TABLE 10. Impact of Drought on Ground-Water Levels.

		Change From Base Period		
Hydrologic Region	**Base Period (m/year)**	**Severe Drought (m/year)**	**Moderate Drought (m/year)**	**Slight Drought (m/year)**
Sacramento	0.079	−0.17	−0.12	−0.055
Eastside	0.295	−0.33	−0.11	−0.078
Delta	−0.003	−0.43	−0.34	−0.258
San Joaquin	0.216	−0.58	−0.25	−0.134
Tulare	0.023	−1.41	−1.12	−0.575
Central Valley	0.094	−0.77	−0.55	−0.288

Ground-Water Decline and Recovery

The average ground-water level of the Central Valley falls 46 m (140 ft) by the end of the severe 60-year drought scenario, 33 m (101 ft) by the end of the moderate drought scenario, and 17 m (53 ft) by the end of the slight drought scenario (Table 11). Ground-water levels drop more in the San Joaquin and Tulare Basins than the other regions due primarily to the larger increase in pumping for these regions. The Tulare Basin experiences the largest decline, ranging from 35 m (105 ft) in the slight drought scenario to 84 m (258 ft) in the severe drought scenario.

The simulations included a 30-year "recovery period" to explore how Central Valley aquifers respond to a return to normal rainfall and irrigation conditions. After the severe 60-year drought, the average ground-water level in the Central Valley rises 8 m (26 ft) over the 10-year recovery period (Table 11), a recovery of only 18%. The average Central Valley ground-water level recovers 15% after a moderate 60-year drought and 21% after a light 60-year drought. In general, ground-water levels recover fairly rapidly in the Sacramento Basin, Eastside Drainage, and San Joaquin Basin, and very slowly in the Tulare Basin (Figure 2). A large portion of the Tulare Basin has experienced chronic overdraft as ground-water withdrawals have often exceeded recharge (CDWR, 2003). The simulated recovery rates suggest that the Tulare Basin would not achieve pre-drought ground-water levels for at least 30 years, if ever. The other regions experience more rapid rates of ground-water recovery, and simulation results suggest these regions would likely achieve pre-drought ground-water levels relatively rapidly after a drought.

CONCLUSIONS

Drought simulations for a set of specified scenarios were performed by constructing reservoir releases

TABLE 11. Change in Average Ground-Water Level During a 60-Year Drought and After a 30-Year Recovery Period.

Hydrologic Region	Severe 60-Year Drought			Moderate 60-Year Drought			Slight 60-Year Drought		
	End	Recovery		End	Recovery		End	Recovery	
	(m)	(m)	(%)	(m)	(m)	(%)	(m)	(m)	(%)
Sacramento	−10	5.9	59	−7.4	3.9	53	−3.3	2.0	60
Eastside	−20	15	72	−6.9	6.6	96	−4.7	5.9	>100
San Joaquin	−35	21	59	−15	8.8	59	−8.0	7.9	1
Tulare	−84	2.6	3	−67	3.3	5	−35	2.3	7
Central Valley	−46	8.4	18	−33	4.9	15	−17	3.6	21

and surface water diversions with CDWR's *CALSIM* model, and simulating the land surface, stream and aquifer response with CDWR's California Central Valley Ground water-Surface Water Simulation Model (*C2VSIM*). Three types of drought intensities were considered, 30% (light), 50% (moderate), and 70% (severe) reductions in inflows to reservoirs, with reduced flow durations ranging from 10 to 60 years. Central Valley surface flow diversions decreased by 12% under the slight drought scenario, and 38% under the severe drought scenario. In response to reduced surface water diversions and reduced rainfall, ground-water pumping increased by 27% under the slight drought and by 71% under the severe drought. Net discharge from aquifers to rivers decreased by 23% for slight drought to 68% for severe droughts, and aquifer recharge decreased by 4% for slight droughts to 48% for severe droughts. The impacts on ground-water levels correlate with changes in ground-water storage, but are complicated by the compensating increase in pumping for highly irrigated regions (e.g., the San Joaquin Basin and Tulare Basin) with average Central Valley ground-water levels falling 17 m (53 ft) under the slight drought and 46 m (140 ft) under the severe drought. Simulated ground-water levels do not fully recover within 30 years after the end of the severe drought, and for the moderate and slight droughts a new equilibrium appears to be established.

This study employed stationary 2003-level agricultural and urban water demands to investigate the response of the ground-water flow system to long-term droughts. Future climate changes are expected to include many complex impacts on California's Central Valley that were not addressed in this study, including changes in the amount and timing of crop water demands as a result of increased mean temperature and evapotranspiration and increased atmospheric carbon (Brumbelow and Georgakakos, 2007; Kay and Davies, 2008), and changes in the timing and amounts of streamflow to reservoirs (Miller *et al.*, 2003; Hayhoe *et al.*, 2004; CDWR 2006; Milly *et al.*, 2008). The impacts of these changes are difficult to assess owing to the numerous and dynamic aspects of the ground-water flow system, including the spatial and temporal variability of recharge and interactions with surface water bodies and the land surface (Alley *et al.*, 2002). This is further complicated because local changes in ground-water pumping, recharge, and other aspects of the hydrologic system may be significantly affected by changes in policies, societal values, and economic and technological factors (Loaiciga, 2003; Holman, 2006; King *et al.*, 2008). This reduced form study gives a quantitative response to specified droughts that act as analogues to snowpack reduced inflows to reservoirs, and illustrates the general impacts of climatic events on water storage under present day land use and population demands. Further study is required to determine the degree to which changes in agricultural demands in response to economic pressures would reduce ground-water depletion and promote more rapid recovery to pre-drought ground-water levels.

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