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Drivers of drought-induced shifts in the water balance through a Budyko approach

Tessa Maurer et al.

Correspondence to: Tessa Maurer (tmaurer13@berkeley.edu)

Supplement

S1 Data

Table S1: Precipitation corrections by basin

Basin	Adjustment, mm	% of long-term average precip
Shasta	-85.7	-8.6 %
Feather	-81.5	-6.9 %
Yuba	-85.6	-5.0 %
American	-62.3	-4.6 %
Cosumnes	49.8	5.0 %
Mokelumne	-66.2	-5.1 %
Stanislaus	-2.4	-0.2 %
Tuolumne	-57.2	-5.2 %
Merced	-7.1	-0.7 %
San Joaquin	-28.9	-3.0 %
Kings	-25.3	-2.7 %
Kaweah	-44.2	-5.0 %
Kern	26.2	5.0 %
Tule	-18.8	-2.7 %

Table S2: Annual subsurface storage withdrawals as a fraction of precipitation

Basin	Avg $\pm$ std dev (all years)	Avg $\pm$ std dev (droughts)	Max annual (all years)
Shasta	0.015 $\pm$ 0.012	0.016 $\pm$ 0.011	0.046
Feather	0.040 $\pm$ 0.032	0.043 $\pm$ 0.036	0.120
Yuba	0.015 $\pm$ 0.014	0.015 $\pm$ 0.014	0.055
American	0.026 $\pm$ 0.022	0.028 $\pm$ 0.023	0.087
Cosumnes	0.068 $\pm$ 0.054	0.078 $\pm$ 0.061	0.227
Mokelumne	0.015 $\pm$ 0.013	0.016 $\pm$ 0.014	0.047
Stanislaus	0.021 $\pm$ 0.019	0.025 $\pm$ 0.021	0.074
Tuolumne	0.020 $\pm$ 0.018	0.023 $\pm$ 0.019	0.070
Merced	0.032 $\pm$ 0.030	0.045 $\pm$ 0.037	0.112
SanJoaquin	0.023 $\pm$ 0.016	0.026 $\pm$ 0.019	0.055
Kings	0.018 $\pm$ 0.014	0.017 $\pm$ 0.016	0.057
Kaweah	0.020 $\pm$ 0.016	0.023 $\pm$ 0.019	0.056
Kern	0.082 $\pm$ 0.076	0.111 $\pm$ 0.098	0.302
Tule	0.116 $\pm$ 0.089	0.132 $\pm$ 0.115	0.311

Table S3: Full-natural flow gauges

Basin	Gauge name	CDEC gauge code
Shasta	Sacramento River above Bend Bridge	SBB
Feather	Feather River at Oroville	FTO
Yuba	Yuba River near Smartville	YRS
American	American River at Folsom	AMF
Cosumnes	Cosumnes River at Michigan Bar	CSN
Mokelumne	Mokelumne - Mokelumne Hill	MKM
Stanislaus	Stanislaus River - Goodwin	SNS
Tuolumne	Tuolumne River - La Grange Dam	TLG
Merced	Merced River near Merced Falls	MRC
San Joaquin	San Joaquin River below Friant	SJF
Kings	Kings River - Pine Flat Dam	KGF
Kaweah	Kaweah River - Terminus Dam	KWT
Kern	Kern River - below Isabella	KRI
Tule	Success Dam	SCC

S2 *abcd* model results

The *abcd* model (Thomas, 1981) can be understood under a generalized proportionality hypothesis framework (Wang and Tang, 2014). The primary equation assumes PET or "evaporation opportunity", Y, for each time step as a function of available water and two parameters, a and b. The former ranges from zero to one and can be understood physically as the tendency for runoff to occur in the basin before the soil is saturated. The latter is the maximum evaporation opportunity, measured in depth. Soil storage in the model is calculated under the assumption that actual ET from the soil occurs in proportion to PET, Y. The model goes on to separate direct runoff from groundwater recharge based on parameters c and d, allowing total streamflow and baseflow to be calculated as well. However, as the primary goal of using the *abcd* model here was calculating change in soil storage, we did not use parameters c or d. For more details on the *abcd* model and its use in conjunction with the Budyko model, see Du et al. (2016).

A basic sensitivity test was performed for the initial conditions for soil and groundwater storage, which were tested one at a time. The value and direction of shift in ω are robust to initial values ranging between 5 and 500 mm, to reflect the order of magnitude of maximum dry-season storage water draw down that has been reported in the Sierra (Roche et al., 2020). Only in one basin, the San Joaquin, did ω show a shift in the opposite direction for initial soil storage values of 100 and 500 mm.

Table S4: *abcd* model final calibrated parameters

Basin	**Parameter a^a**	**Parameter b, mm^b**
Shasta	1.000	806
Feather	0.944	1402
Yuba	0.991	1450
American	0.979	1355
Cosumnes	0.956	1450
Mokelumne	1.000	1076
Stanislaus	0.985	1030
Tuolumne	0.995	1122
Merced	0.999	1396
San Joaquin	0.983	780
Kings	0.993	670
Kaweah	0.996	782
Kern	0.993	759
Tule	0.985	1442

[a]Parameter a reflects the propensity of a basin to generate runoff before the soil is saturated.
[b]Parameter b is the maximum possible evapotranspiration per time step.

Table S5: *abcd* model performance with respect to runoff

Basin	**Nash-Sutcliffe Efficiency**	**Runoff relative error**
Shasta	0.851	0.135
Feather	0.882	0.114
Yuba	0.916	0.116
American	0.896	0.140
Cosumnes	0.880	0.193
Mokelumne	0.938	0.108
Stanislaus	0.939	0.107
Tuolumne	0.931	0.104
Merced	0.747	0.237
San Joaquin	0.950	0.109
Kings	0.930	0.126
Kaweah	0.946	0.124
Kern	0.559	0.357
Tule	0.780	0.231

Table S6: Average annual ΔS results by basin

Basin	**All years, mm**	**Withdrawal years, mm**	**Replenishment years, mm**
Shasta	-0.77	-15.0	13.5
Feather	-0.71	-47.8	40.9
Yuba	-1.21	-21.2	28.0
American	-1.12	-32.9	30.7
Cosumnes	-0.06	-50.2	73.2
Mokelumne	-1.33	-16.3	20.5
Stanislaus	-1.54	-22.3	22.0
Tuolumne	-1.50	-20.0	22.4
Merced	-1.51	-26.5	26.8
SanJoaquin	-1.51	-19.4	21.5
Kings	-1.41	-15.0	18.5
Kaweah	-1.59	-15.1	18.2
Kern	-2.71	-35.8	34.7
Tule	-0.14	-72.0	71.7

S3 Statistical significance of water balance shifts

Table S7: Results of Kolmogorov-Smirnov tests comparing drought and non-drought distributions

Basin	**PET/(P-ΔS) *p*-values**	**ET/(P-ΔS) *p*-values**	**ET/PET *p*-values**
Shasta	2.07E-04	3.93E-03	4.57E-04
Feather	4.57E-04	2.46E-02	8.78E-03
Yuba	1.67E-03	7.51E-03	1.19E-02
American	4.57E-04	5.46E-03	8.06E-04
Cosumnes	3.09E-04	3.09E-04	3.93E-03
Mokelumne	8.06E-04	7.51E-03	1.16E-03
Stanislaus	2.07E-04	7.51E-03	1.16E-03
Tuolumne	2.07E-04	3.93E-03	1.16E-03
Merced	2.07E-04	8.06E-04	3.93E-03
San Joaquin	2.07E-04	2.81E-03	1.60E-02
Kings	2.07E-04	8.06E-04	1.16E-03
Kaweah	8.06E-04	8.06E-04	1.60E-02
Kern	3.93E-03	8.06E-04	4.81E-02
Tule	9.92E-06	4.79E-05	1.19E-02

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