Geophysical Research Letters

Supporting Information for

Efficiency of the Summer Monsoon in Generating Streamflow within a Seasonally Snow-Dominated Headwater Basin of the Colorado River

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Introduction

Additional East River (ER) model parameterization, calibration and output given in tabular and graphical form. Tables and figures are described in the main manuscript.

S.1. Hydrologic Model Parameterization

Table S1. East River sub-basin characteristics (modified from Carroll *et al.*, 2018)

Basin ID	name	Area[a]	Elev[b]	Relief[b]	Slope[b]	Aspect[b]	Annual Precip.[c]	Peak SWE[c]	Vegetation Type[d]			Total Forest[d]	Tree Density[e]
									Barren	Conifer	Aspen		
1	EAQ	5.27	3349	900	24	127	1,513	893	0.25	0.58	0.04	0.62	23
2	Quigley	2.55	3380	915	22	85	1,513	1,010	0.23	0.61	0.01	0.61	26
3	Rustlers	14.78	3490	1,118	22	196	1,573	907	0.24	0.54	0.00	0.54	18
4	Bradley	3.82	3504	1,107	22	242	1,502	917	0.41	0.50	0.00	0.51	20
5	Rock	3.57	3375	931	16	119	1,537	926	0.08	0.72	0.00	0.72	32
6	Gothic	0.90	3379	875	20	164	1,516	923	0.23	0.70	0.00	0.70	33
7	Marmot	0.38	3152	544	18	232	1,436	668	0.02	0.87	0.06	0.93	42
8	Avery	0.60	3390	916	28	243	1,321	687	0.34	0.52	0.02	0.54	21
9	Copper	23.67	3528	1,242	25	199	1,355	867	0.50	0.36	0.02	0.38	14
10	Pumphouse	84.73	3346	1,364	21	175	1,413	984	0.27	0.48	0.09	0.57	22

[a] km^2

[b] mean values for elevation (m), slope (%) and aspect (degrees); relief (m)

[c] simulated annual mean (mm) 1987-2019, SWE = snow water equivalent

[d] fraction of basin area

[e] area weighted fraction

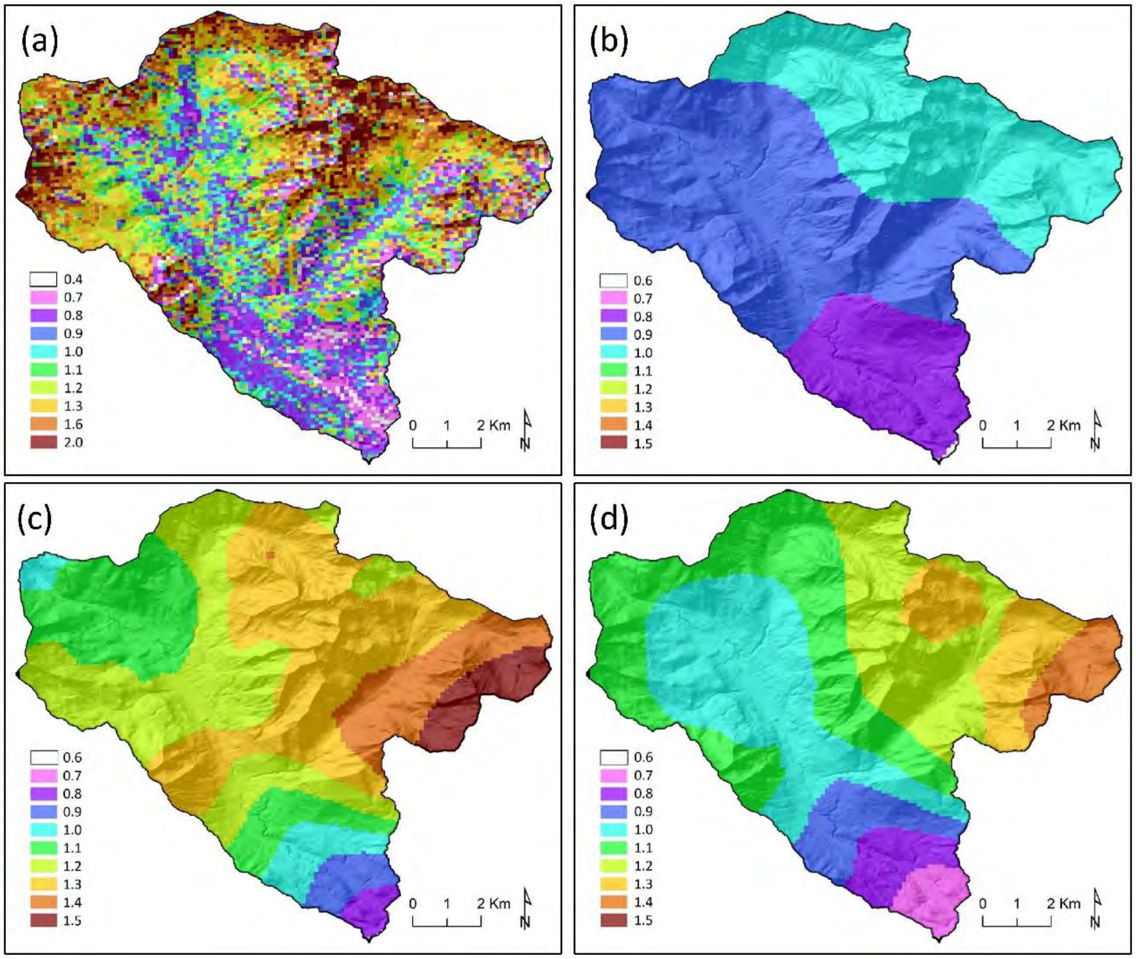

Figure S1. Ratios used to spatially distribute Schofield (a) snow water with ratios determined using snow water equivalent derived from LiDAR snow depths obtained during peak snow water equivalent on an average snow year April 4, 2016 (Painter et al., 2016) and adjusted for snow losses and melt prior to flight; and rain based on monthly average 30-year (1981-2010) PRISM raster maps (800 m) (OSU, 2012) (b) July, (c) August and (d) September.

S.2. Hydrologic Model Calibration and Verification

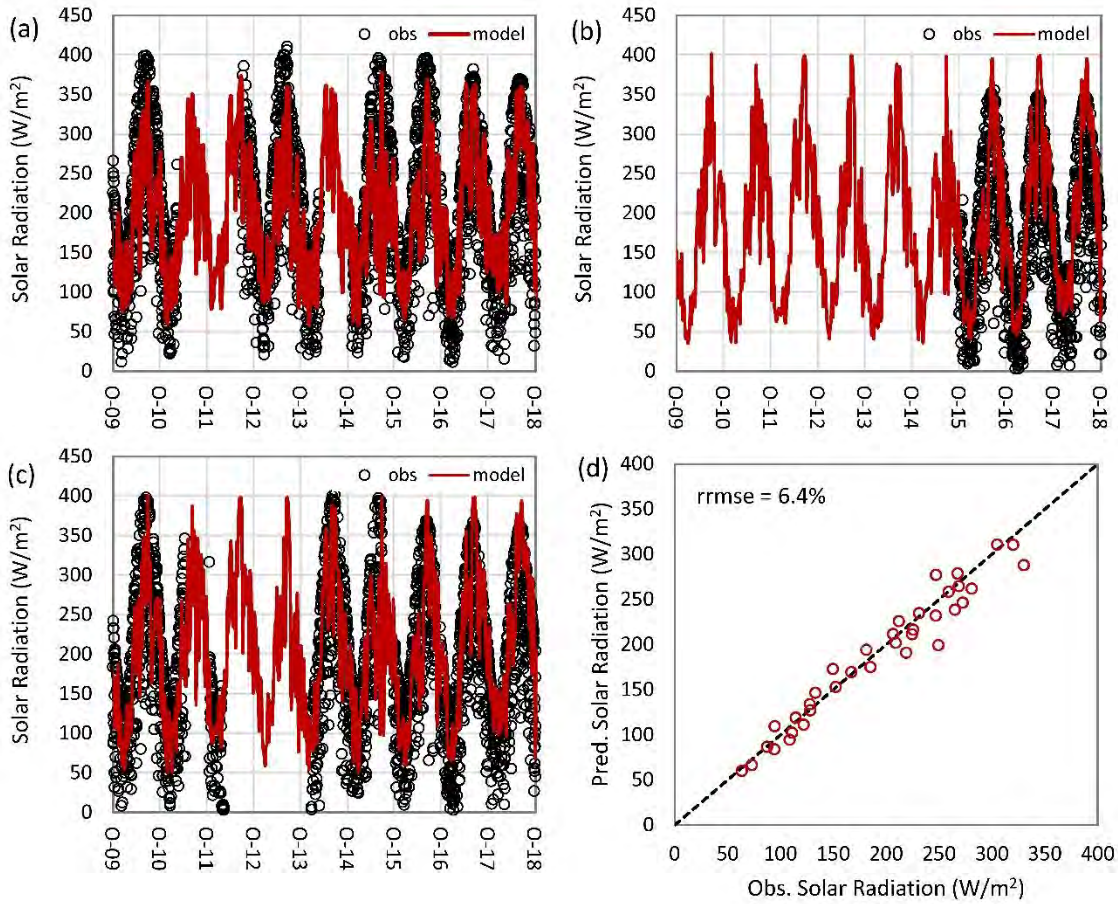

Figure S2. Updated simulated solar radiation results first presented by (Carroll et al., 2019). Observed and modeled solar radiation at Rocky Mountain Biological Laboratory (RMBL) weather stations (a) Kettle Ponds (KP), (b) billy barr (BB) and (c) Judd Falls (JF). Calibration accomplished adjusting the PRMS monthly degree-day slope parameter (dday_slope) to minimize the relative root mean squared error (rrmse) of mean monthly solar radiation at each station. Snodgrass (SG) not included in calibration. Model consistently over predicts this location by 125±33 W/m^2 with over prediction likely due to tall conifer forest (>10 m) encroaching on tower affecting observations. Locations provided in the manuscript Figure 1. Observed data available to the public at https://www.digitalrmbl.org/collections/weather-stations/.

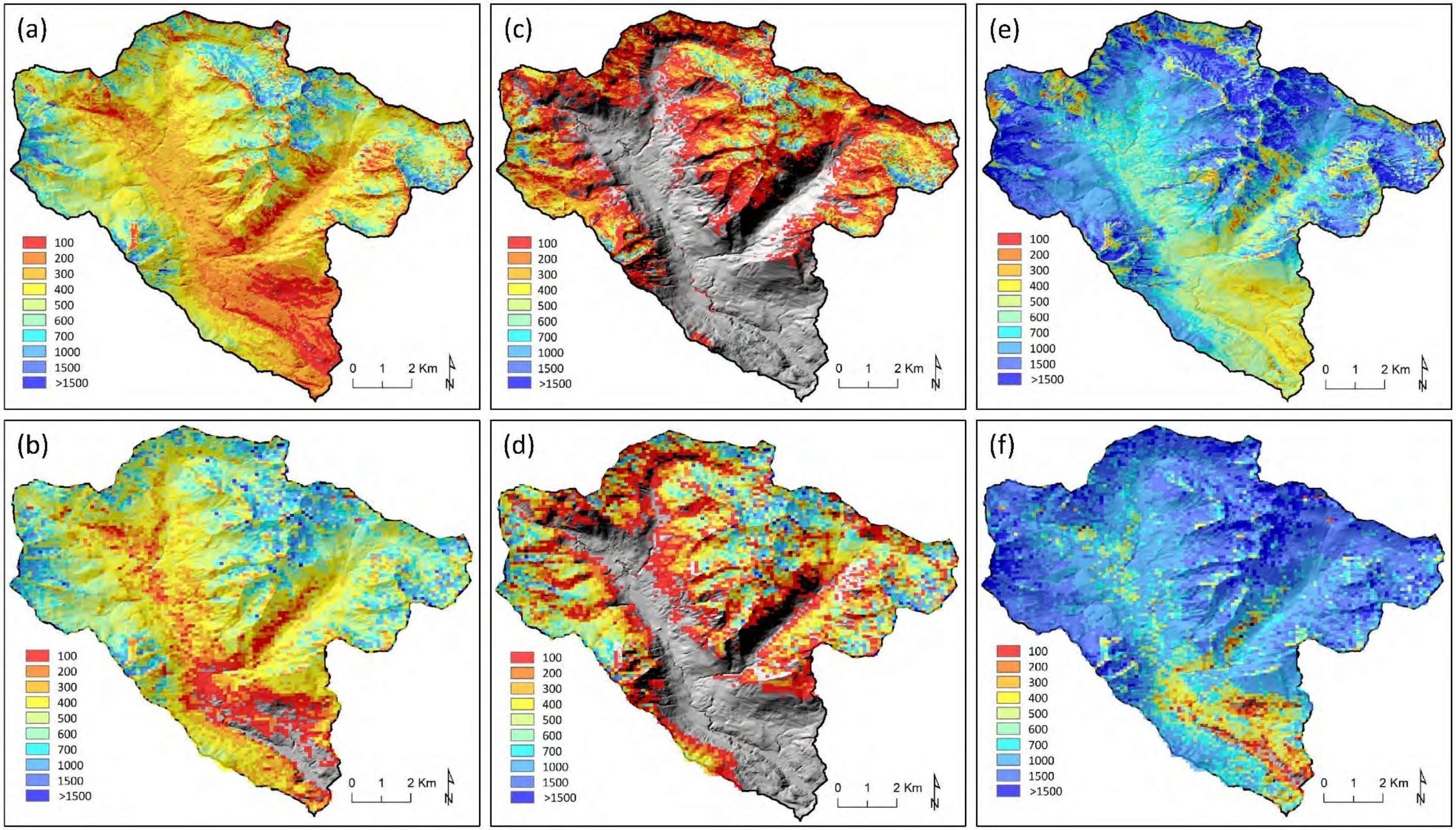

Figure S3. Validation of snow water equivalent (SWE, mm) between Airborne Snow Observatory (ASO, 50-m resolution) and PRMS (100-m resolution) for March 30, 2018 (a) ASO, (b) PRMS; May 24, 2018 (c) ASO and (d) PRMS, and April 7, 2019 (e) ASO, (f) PRMS

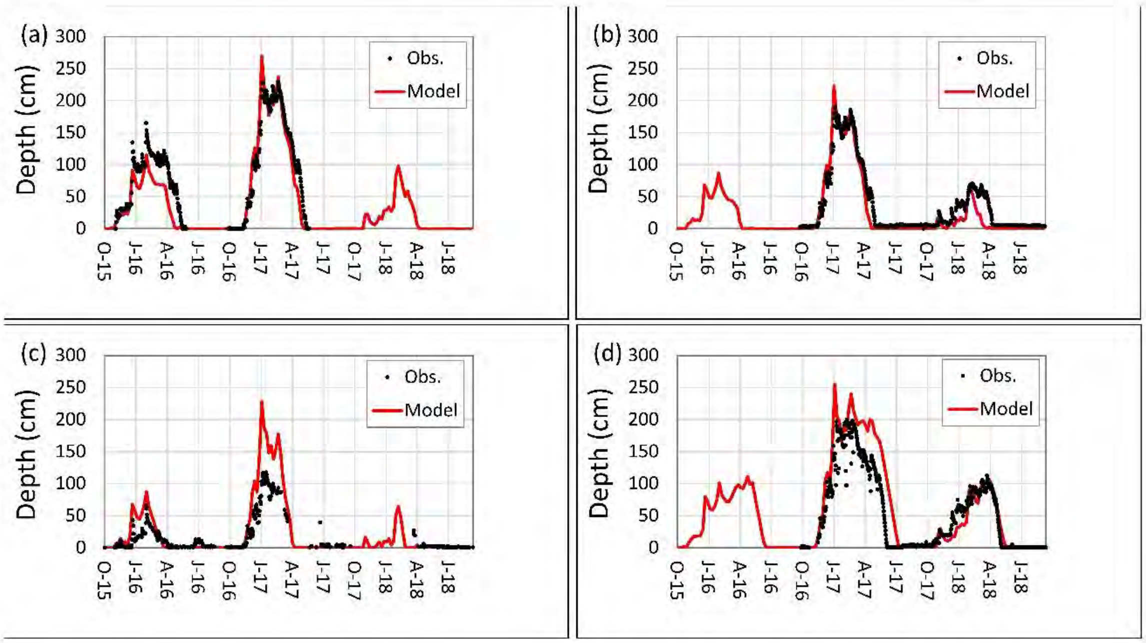

Figure S4. Snow depth comparison between observed weather stations and modeled, (a) billy barr (BB), (b) Judd Falls (JF), (c) Kettle Ponds (KP) and (d) Snodgrass (SG). Locations provided in the manuscript Figure 1. Simulated results updated from (Carroll et al., 2019). Observed data available to the public at https://www.digitalrmbl.org/collections/weather-stations/.

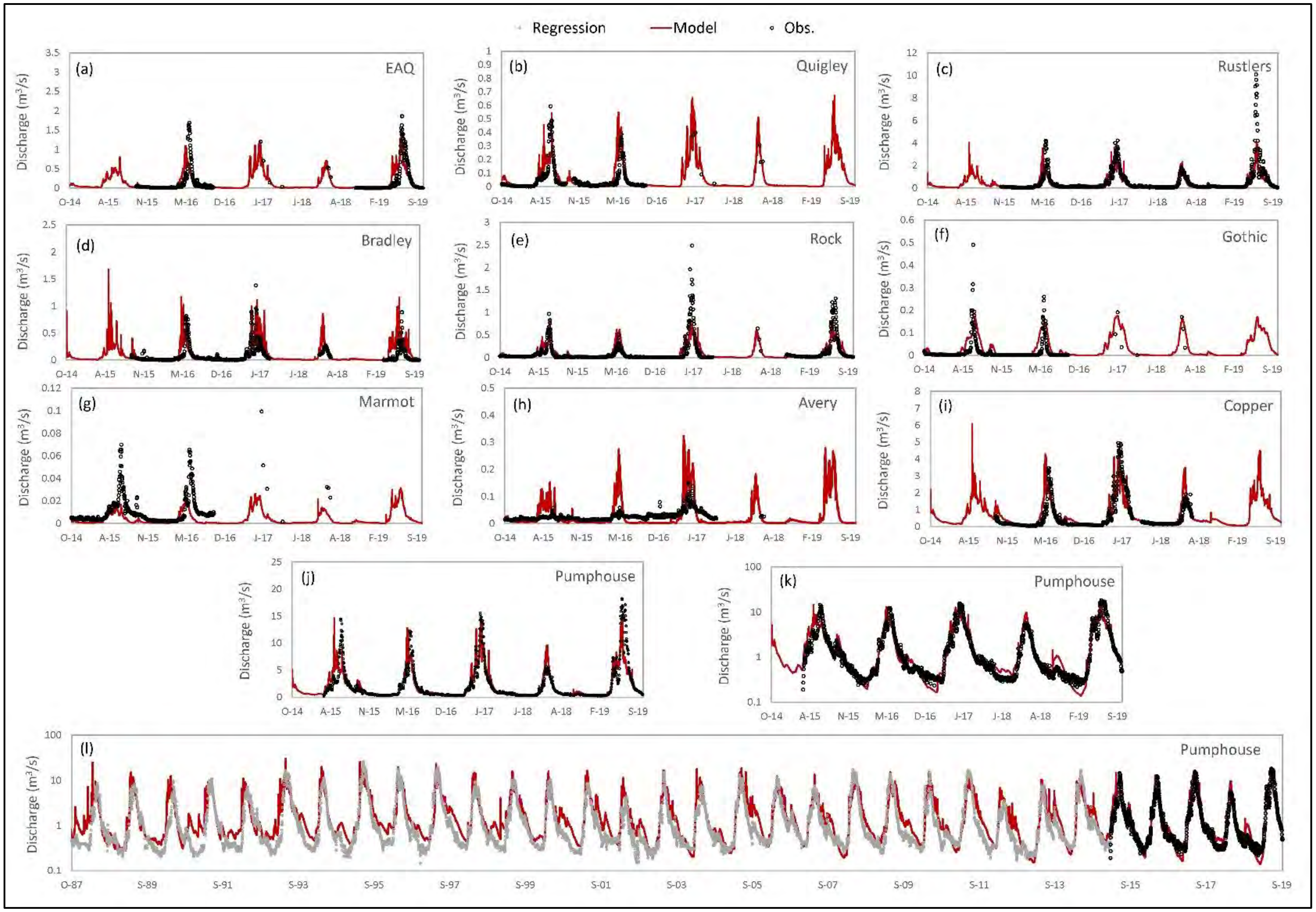

Figure S5. A comparison of daily observed and modeled streamflow for the period of record with data (a) EAQ, (b) Quigley, (c) Rustlers, (d) Bradley, (e) Rock, (f) Gothic, (g) Marmot, (h) Avery, (i) Copper, (j) Pumphouse, (k) Pumphouse, log streamflow and (l) Pumphouse log streamflow for entire simulation with estimated flow from USGS stream gauge (ID 09112500) located 25 km downstream.

S.3. Hydrologic Model Results

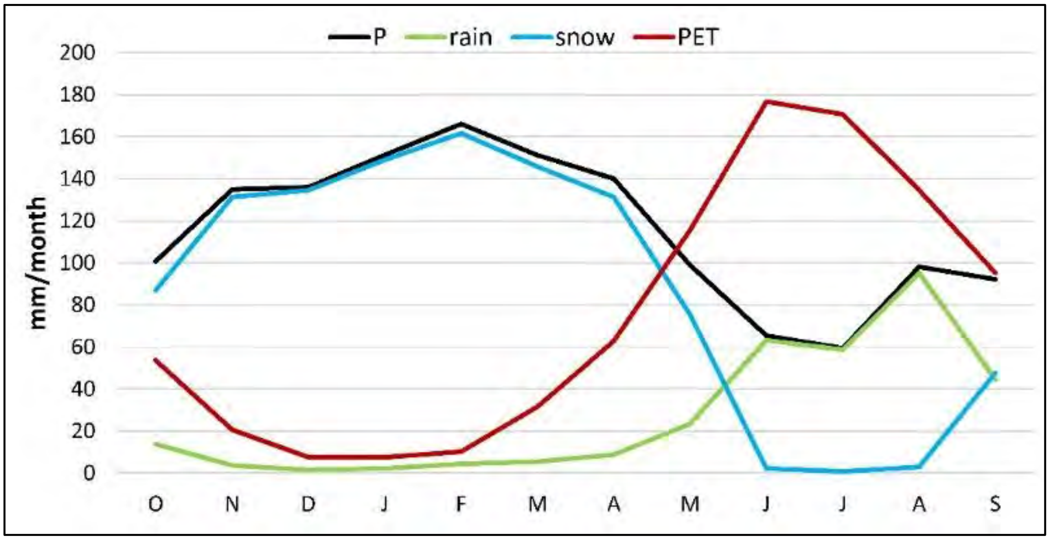

Figure S6. East River basin scale average simulated monthly precipitation (P) and potential evapotranspiration (PET). Precipitation is divided into rain and snow contributions

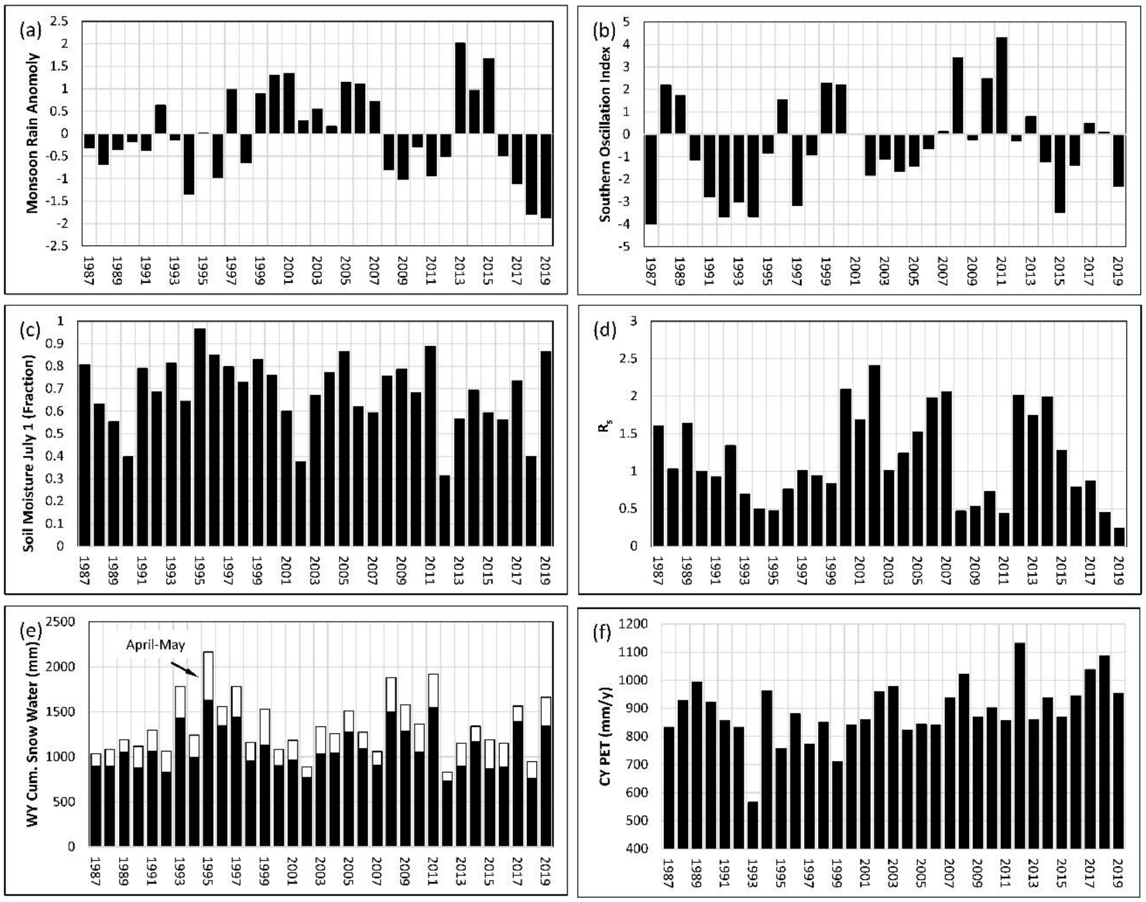

Figure S7. East River simulated (a) monsoon rain (July-September) anomalies (z-score), (b) Southern Oscillation Index (Trenberth, 2020), (c) soil moisture fraction July 1, (d) the ratio of monsoon rain to spring snowfall, R_s (c) water year (Oct-Sept) cumulative snow water input with the spring snow contributions in April and May identified, (d) calendar year potential evapotranspiration (PET).

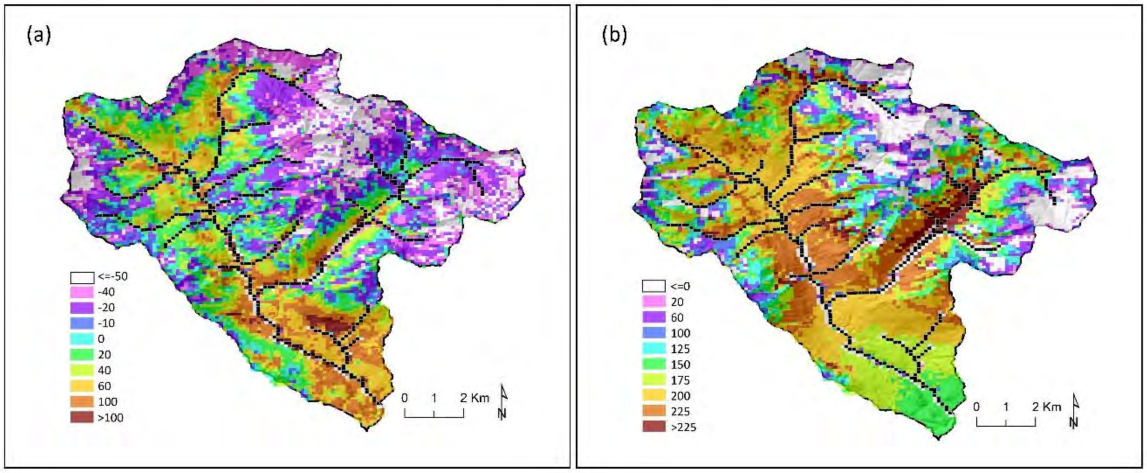

Figure S8. Spatial differences in 1998 annual total evapotranspiration (mm/y) defined as baseline – scenario for (a) no spring snow in April and May, (b) no monsoon rain July-September. Note that color code scale varies, and a negative value indicates an increase as a result of removing seasonal water input. Black model cells are simulated river cells.

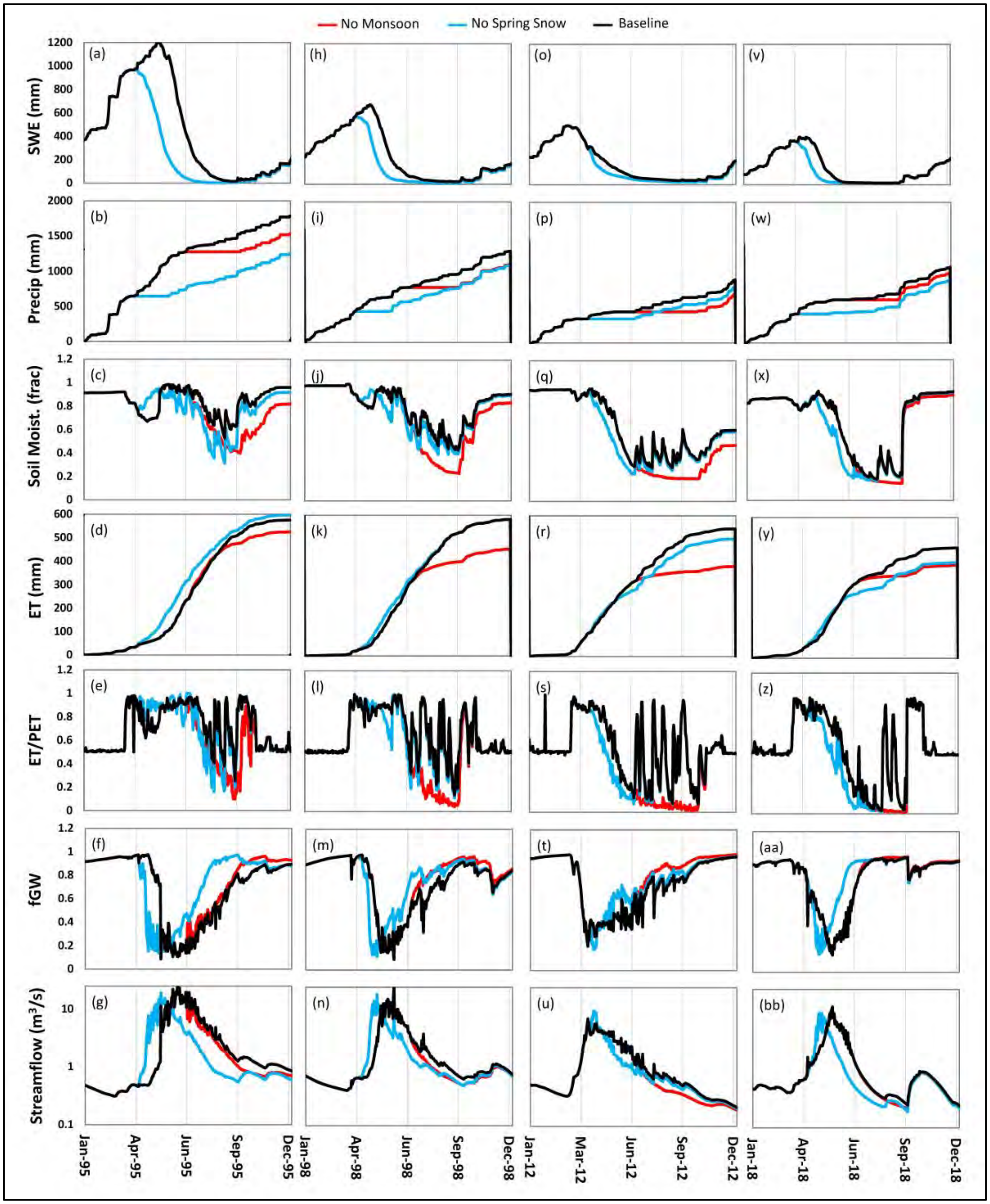

Figure S9. Simulated basin-scale daily water budget items for baseline and scenarios removing spring snow (April-May) and monsoon rain (July-September) for years: (a-g) 1995 (h-n) 1998, (o-u) 2012, and (v-bb) 2018. SWE = snow water equivalent, fGW = fraction of groundwater contributed to stream.

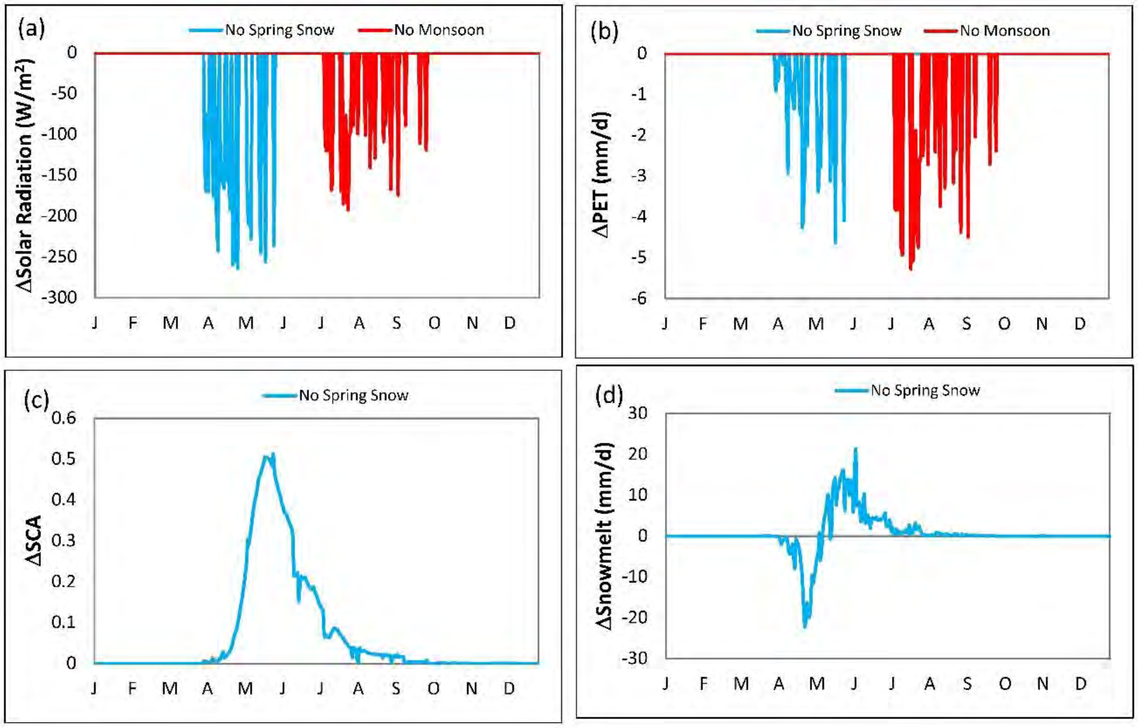

Figure S10. Temporal changes (Δ) for year 1998 between baseline and removal of either spring snow or monsoon rain: (a) solar radiation, (b) potential ET, PET, (c) snow covered area, SCA, and (d) snowmelt. For clarity, a negative value indicates increases as a result of removing seasonal water input.

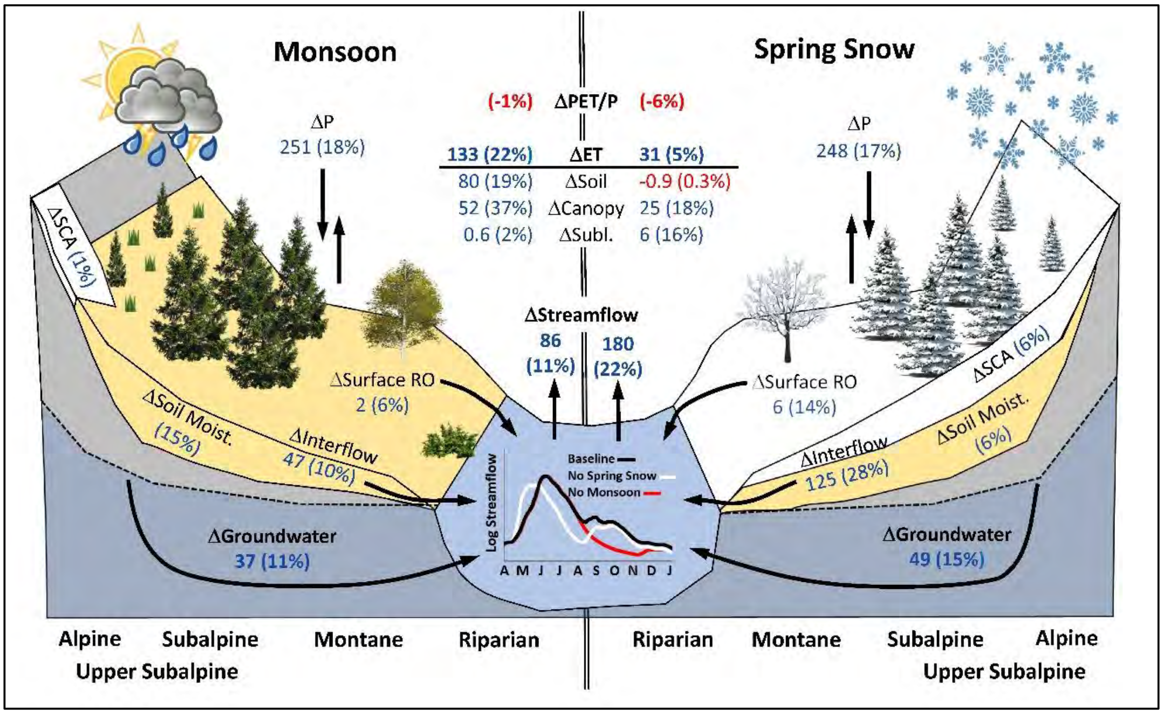

Figure S11. Average annual changes in water fluxes (and snow, soil storage) between the baseline (1987-2019) and scenarios with no monsoon (July-September) and no spring (April-May) precipitation. Blue (red) font = increase (decrease) due to added water input. SCA = snow covered area. RO = runoff.

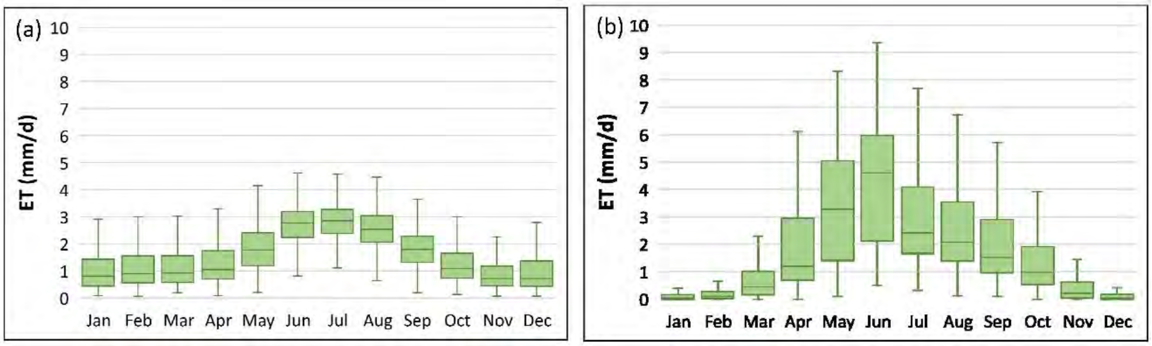

Figure S12. A comparison of average monthly evapotranspiration (ET) rates from daily aggregated totals for (a)Ameriflux stations Niwot Ridge LTER (US-NR1), years 1998-2019, (b) simulated with PRMS, years 1987-2019. Ameriflux 30-min latent heat flux data available at ameriflux.lbl.gov.

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