Supporting Information for "Intensification of hydrological drought in California by human water management"

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Contents

Introduction

This supporting information contains the methodology for calculation of drought characteristics (Text S1), streamflow validation metrics (Figure S1), time series and scatter plots for selected USGS stations (Figure S2-S5), drought deficit validation for selected drought events (Figure S6) and the comparison between observed and simulated drainage area in PCR-GLOBWB (Figure S7). Table S1 summarizes the goodness-of-fit metric of the five parametric distributions used for extreme value analysis in this study.

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Figure S1.

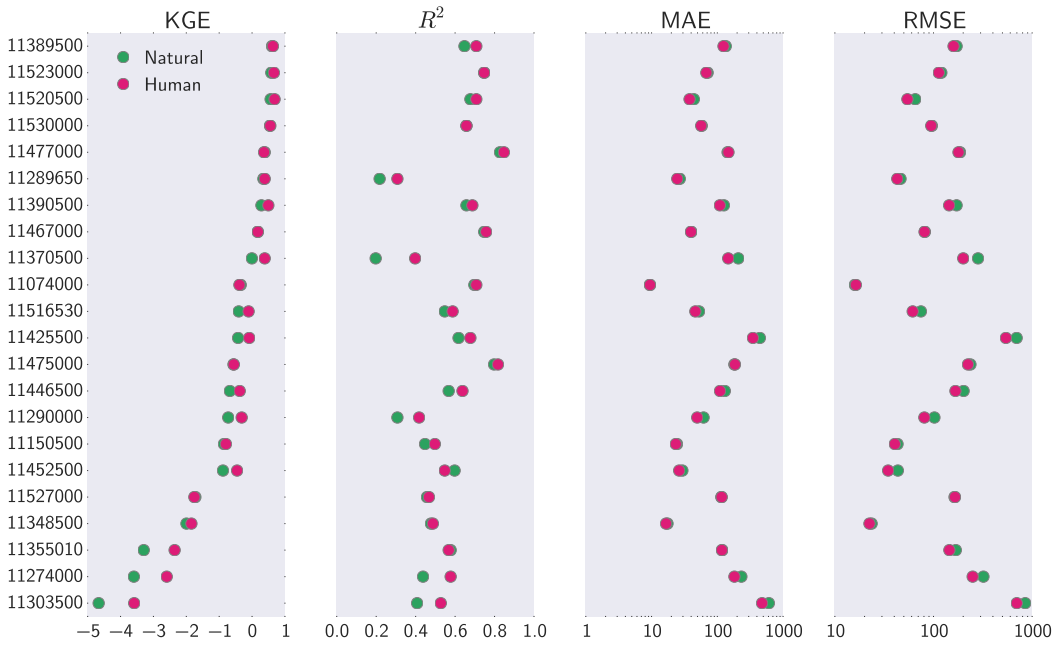

Figure 1. Streamflow validation metrics for 22 selected USGS stations including Kling-Gupta efficiency (KGE), coefficient of determination (R^2), mean absolute error (MAE, m^3/s) and root mean squared error (RMSE, m^3/s).

Figure S2.

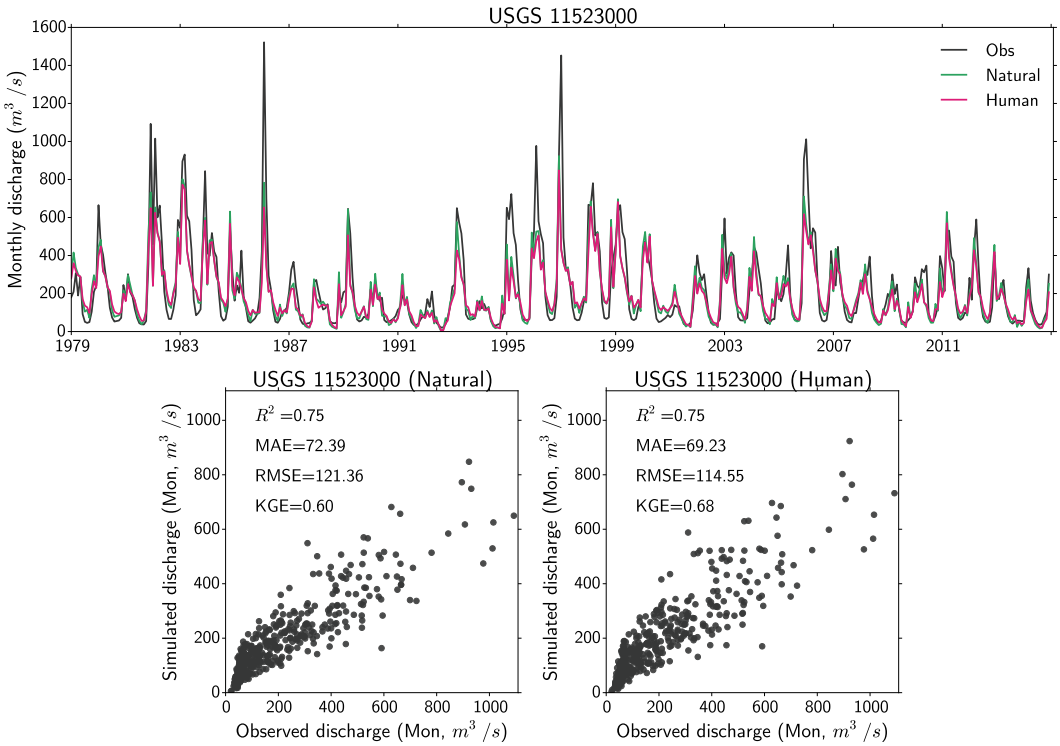

Figure 2. Time series of monthly observed and simulated discharge (top panel) at USGS station 11523000 and the corresponding scatter plots (bottom left: Natural scenario; bottom right: Human scenario).

Figure S3.

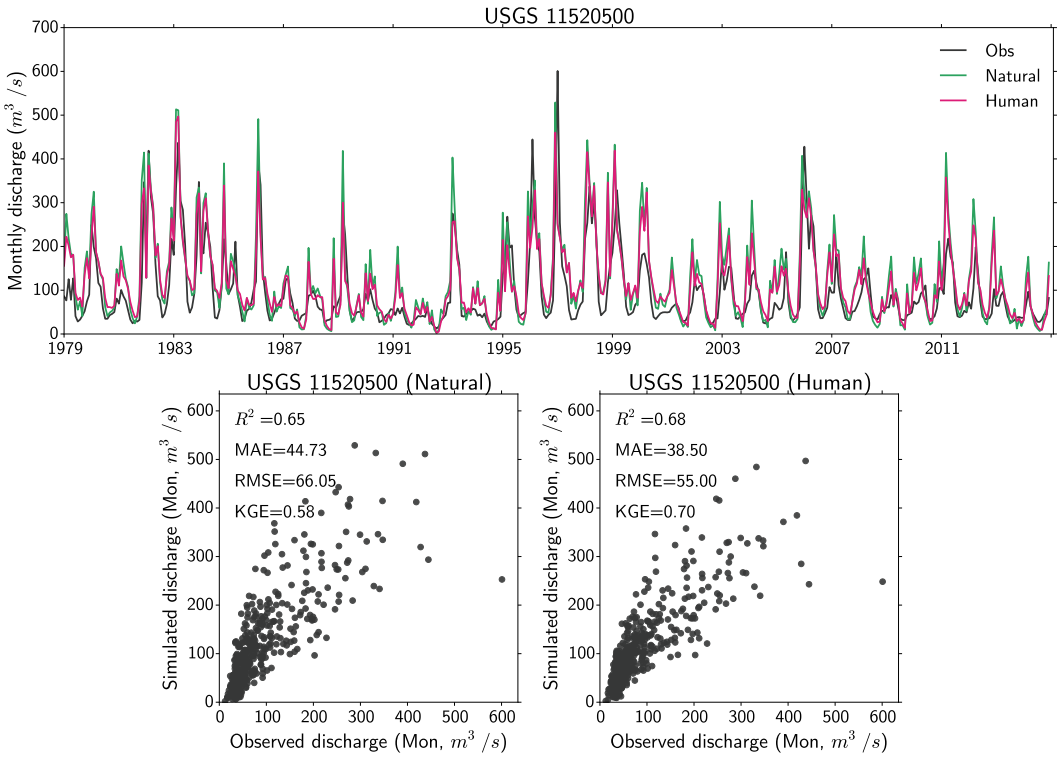

Figure 3. Similar as Figure 2, but for USGS station 11520500.

Figure S4.

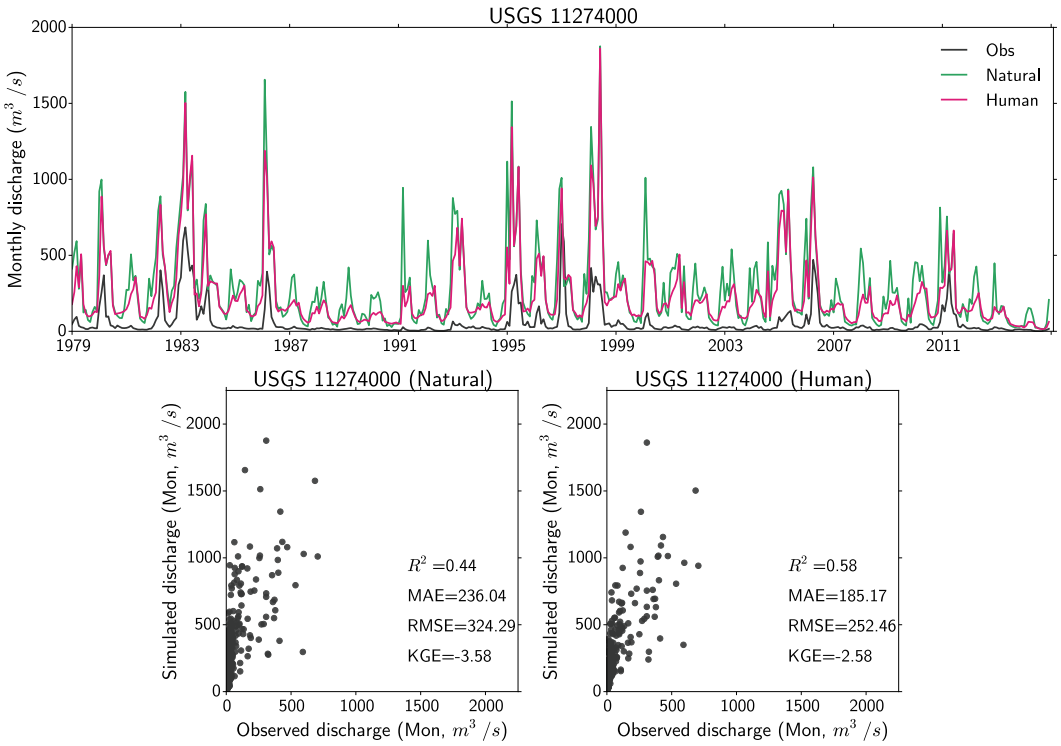

Figure 4. Similar as Figure 2, but for USGS station 11274000.

Figure S5.

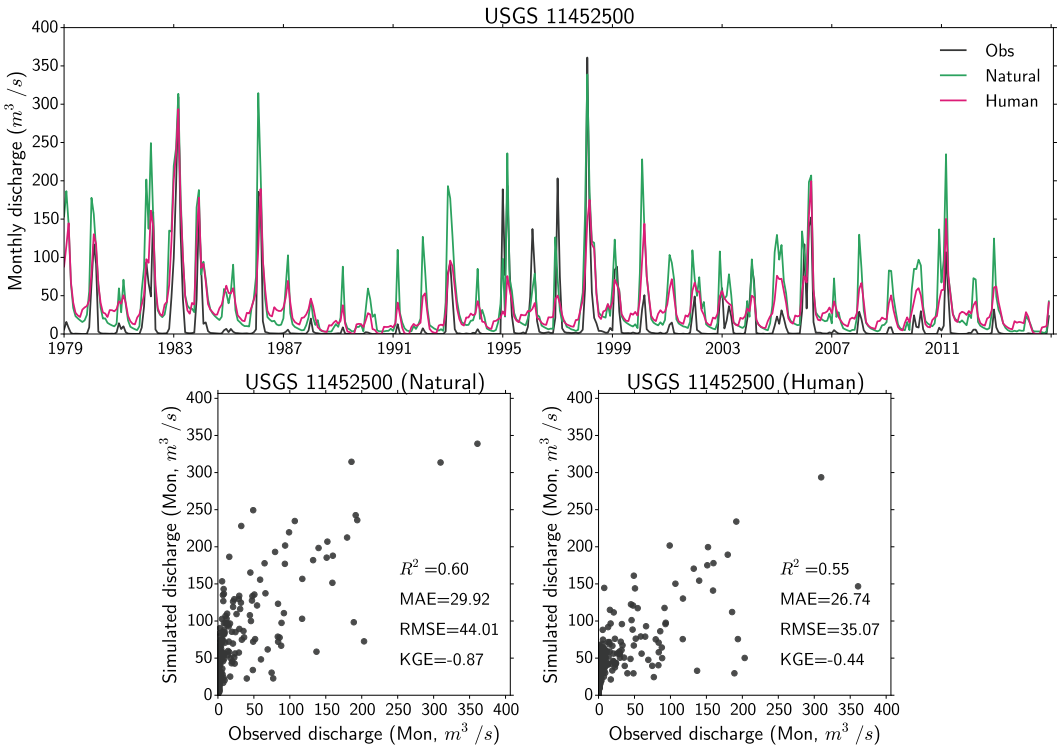

Figure 5. Similar as Figure 2, but for USGS station 11452500.

Figure S6.

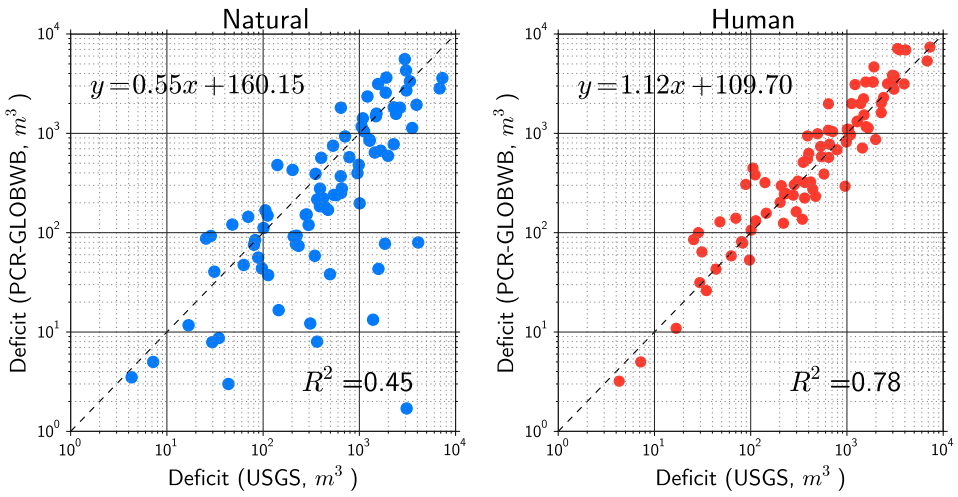

Figure 6. Similar as the middle and right panels of Figure 1 in the main manuscript, but the deficit volume is calculated for selected drought events.

Figure S7.

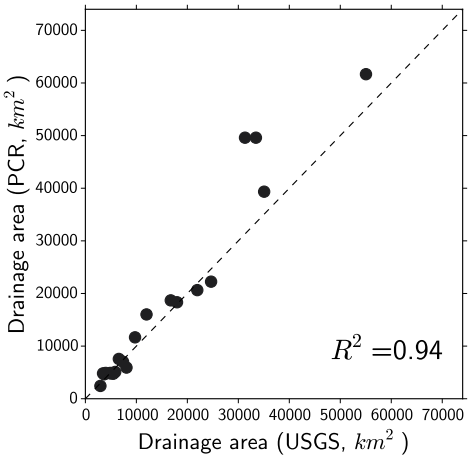

Figure 7. Comparison between the observed drainage area from USGS and the drainage area extracted from PCR-GLOBWB model. As the selected USGS stations may not be located exactly in the river network of PCR-GLOBWB, we manually correct the drainage area between the model and observations.

Text S1. Supplementary methods: Calculation of drought characteristics

1. The binary sequence of hydrological drought occurrence

Let

$$S(t,n) = \begin{cases} 1 & if\ Q(t,n) < Q_{90}(t,n) \\ 0 & if\ Q(t,n) \geq Q_{90}(t,n) \end{cases} \tag{1}$$

where $\{S(t,n)\}$ is the binary discrete time series of the drought state at daily time scale, which only include two integers 0 and 1, with 0 means normal conditions and 1 indicates that drought occurs at location n at a given time t. $Q(t,n)$ is the simulated daily streamfow and $Q_{90}(t,n)$ is the threshold.

2. Drought duration and area in drought (AID)

Drought duration $D(t,n)$ for each event m at grid cell n can be defined as:

$$D_m(n) = \sum_{t=T_f}^{T_l} S(t,n) \tag{2}$$

where T_f and T_l are the first and the last time step when $S(t,n) = 1$. The total area in drought (AID) at time t measures the percentage of the drought area, which can be calculated as:

$$AID(t) = \frac{\sum_{n=1}^{N} D(t,n)}{N} \tag{3}$$

where N is the total number of grid cells. The range of AID is within 0 and 1, with 0 indicating no grid cells are in drought and 1 indicating that all the area is in drought.

3. Drought deficit volume

Drought deficit volume (V, m^3/s) measures how severe the drought is compared to the normal streamflow conditions. It can be defined as:

$$V(t,n) = max(0,\ Q_{90}(t,n) - Q(t,n)) \tag{4}$$

The total drought deficit volume for each drought event m at grid cell n is the accumulation of the consecutive deviation of the streamflow from the threshold over the drought duration period:

$$V_m(n) = \sum_{t=T_f}^{T_l} V(t,n) \tag{5}$$

To allow the comparison among different climatic divisions, standardized drought deficit volume (StDef) is utilized, which is normalized by the mean of $V_m(n)$:

$$StDef(t,n) = \frac{V(t,n)}{\frac{V_m(n)}{T_l - T_f}} = (T_l - T_f)\frac{V(t,n)}{V_m(n)} \tag{6}$$

Table S1.

Table 1. Root mean square error (RMSE) used to evaluate the goodness-of-fit between the empirical and fitted cumulative distribution function (CDF) of the standardized drought deficit volume from 1979 to 2014.

Distribution	Natural scenario	Human scenario
LogNormal	0.051	0.038
GEV_LM	0.057	0.081
Pareto	0.073	0.094
Gamma	0.189	0.064
Weibull	0.153	0.097