Appendix 1: Observed Streamflow

The observed streamflow dataset was acquired from the Bonneville Power Administration (BPA). The original observed data can be downloaded from the following: (https://www.bpa.gov/p/Power-Products/Historical-Streamflow-Data/Pages/Historical-Streamflow-Data.aspx). The dataset has been thoroughly explained in the following BPA report: (https://www.bpa.gov/p/Power-Products/Historical-Streamflow-Data/streamflow/2020%20Level%20Modified%20Streamflow.pdf). The data product that we used for this comparison is the "H" data product, which is the observed dam outflow.

Appendix 2: RColSim Naturalized Streamflow Input Data Set and Simulated Streamflow Data

The input dataset that we used to conduct these simulations was also obtained from the BPA datasets (https://www.bpa.gov/p/Power-Products/Historical-Streamflow-Data/Pages/Daily-Data.aspx). The original observed time series spanned from 1928 to 2018, but for this comparison, RColSim simulations focused on the period between August 1979 to September 2015. The BPA data product that we used is the M product (BPA 2020), which is the most recent BPA NRNI streamflow product. The M dataset is basically the reconstructed naturalized streamflow. In other words, the BPA used the observed streamflow, recorded dam-operation datasets, and irrigation diversions to reconstruct how streamflow would look in the absence of all dams and river-system regulations. The simulation time-step of RColSim is weekly; therefore, the original datasets were converted to weekly before the simulations were conducted.

Appendix 3: Updated Rule Curves

In the current version of RColSim, we updated the rule curves used in the original ColSim Model (Hamlet and Lettenmaier, 1999). The updated rule curves were obtained from the *"Columbia River Basin Detailed Operation Plan for Canadian Dams"* and "*Detailed operating plan for Columbia River Treaty storage*" documents (https://usace.contentdm.oclc.org/digital/collection/p266001coll1/id/3196), developed by the US Army Corps of Engineers' Columbia River Treaty Operating Committee. These documents are updated and released every year; however, to be more consistent with our typical historical simulation periods we used the year 2014 as our baseline year, and incorporated rule curves developed for that year in RColSim.

Appendix 4: Performance Metrics

We used five metrics to evaluate the overall performance of RColSim-simulated dam streamflow outflow against the observed BPA outflow data. These metrics included the Pearson Correlation Coefficient (r), Mean Error (ME), Kling-Gupta Efficiency (KGE), Normalized Root Mean Square of Error (NRMSE), and Volumetric Efficiency (VE). We used the hydroGOF R library to calculate these metrics. The following are the mathematical equations that describe the metrics.

Pearson Correlation Coefficient

Pearson Coefficient demonstrate (r) the strength of correlation between the observed and simulated datasets. Pearson Coefficient is calculated from the following equation:

$$r = \frac{Cov(O,S)}{\sigma_O \sigma_S} \tag{1}$$

Where O and S are the time series of observed and RColSim simulated dam outflow, respectively; and σ_O and σ_S are the standard deviation of the observed and simulated time series.

Mean Error

Mean Error (ME) shows the average difference between the observed and simulated dataset and indicates the direction of model biases. ME can be calculated from the following equation:

$$ME = \frac{1}{N}\sum_{i=1}^{N}(S_i - O_i) \tag{2}$$

Where O and S are the time series of observed and RColSim simulated dam outflow, N is the number of time steps.

Kling-Gupta Efficiency

Kling-Gupta Efficiency (KGE) is an aggregated performance metric that demonstrates how different the two datasets are. The KGE metric calculates the Euclidean distance between the ideal value of these metrics and their current values. There are different versions of KGE metrics (e.g., Gupta et al., 2009; Kling et al., 2012) but metric was calculated from the following relationship:

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \tag{3}$$

Where r is the Pearson Correlation Coefficient; α is the ratio of simulated and observed standard deviation $\left(\frac{\sigma_S}{\sigma_O}\right)$; and β is the ratio between mean of the simulated and observed dataset $\left(\frac{\mu_S}{\mu_O}\right)$.

Normalized Root Mean Square of Error

Normalized Root Mean Square of Error (NRMSE) also provides a metric to compare observed vs. simulated datasets. However, it focuses on the extreme cases of difference between the observed and simulated dataset. NRMSE is calculated using the following equation:

$$NRMSE = 100 \times \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - O_i)^2}}{\sigma_O} \tag{4}$$

Volumetric Efficiency

Volumetric Efficiency (VE) focuses on the relative difference between observed and simulated datasets, and is calculated from the following equation:

$$VE = 1 - \frac{\sum_{i=1}^{N} |S_i - O_i|}{\sum_{i=1}^{N} O_i} \quad (5)$$

Appendix 5: Dam Outflow from Reservoirs Simulated in RColSim

As discussed in the main body of the paper (Figure 1), six major CRB sub-basins are simulated in RColSim. Here, we compare simulated outflow against observed dam outflow at each of these sub-basins. We used two temporal time scales for our comparison: (1) mean monthly flow, which demonstrates RColSim model performance at capturing the overall seasonality regime and magnitude of the recorded dam outflow, and (2) weekly flow, which is the original simulation time-step of RColSim.

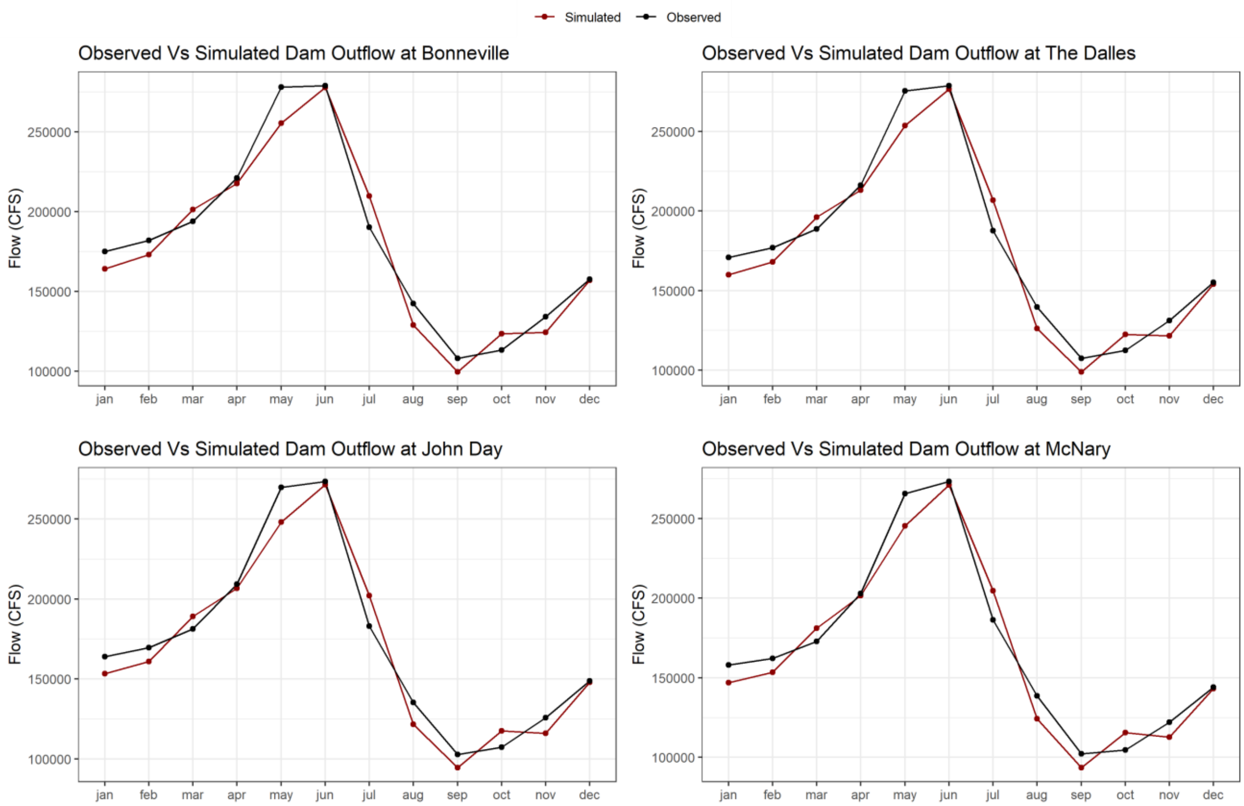

Figure 1. Observed vs. simulated mean monthly dam outflow from dams located in the Lower Columbia

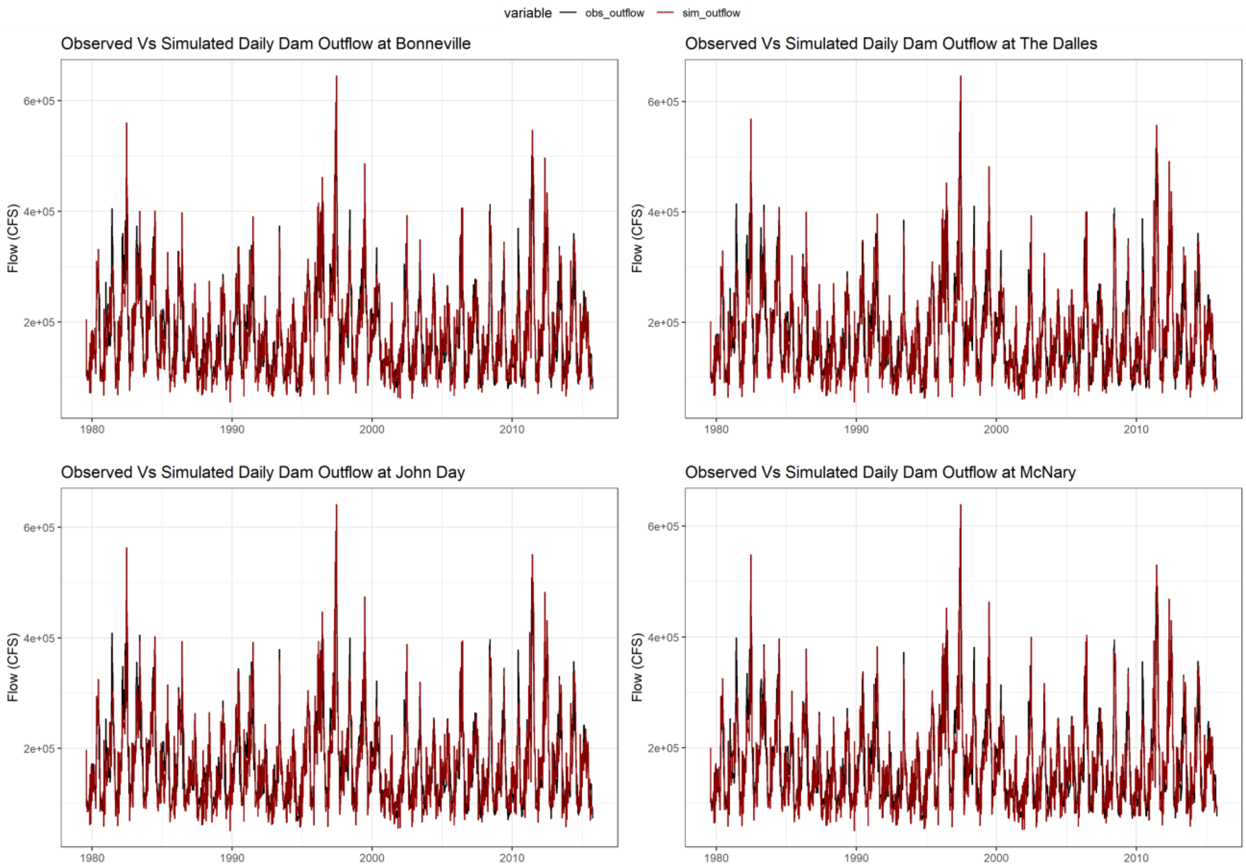

Figure 2. Observed vs. simulated weekly dam outflow from dams located in the Lower Columbia

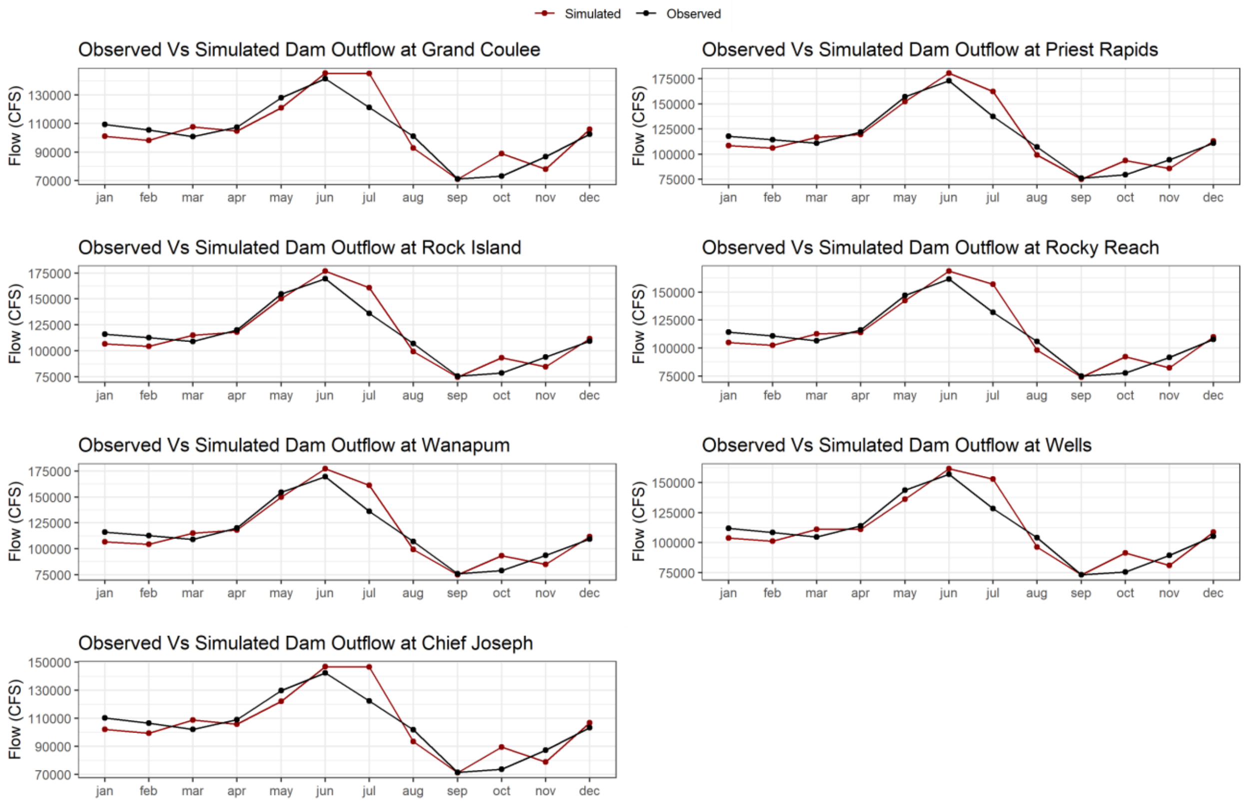

Figure 3. Observed vs. simulated mean monthly dam outflow from dams located in the middle Columbia region

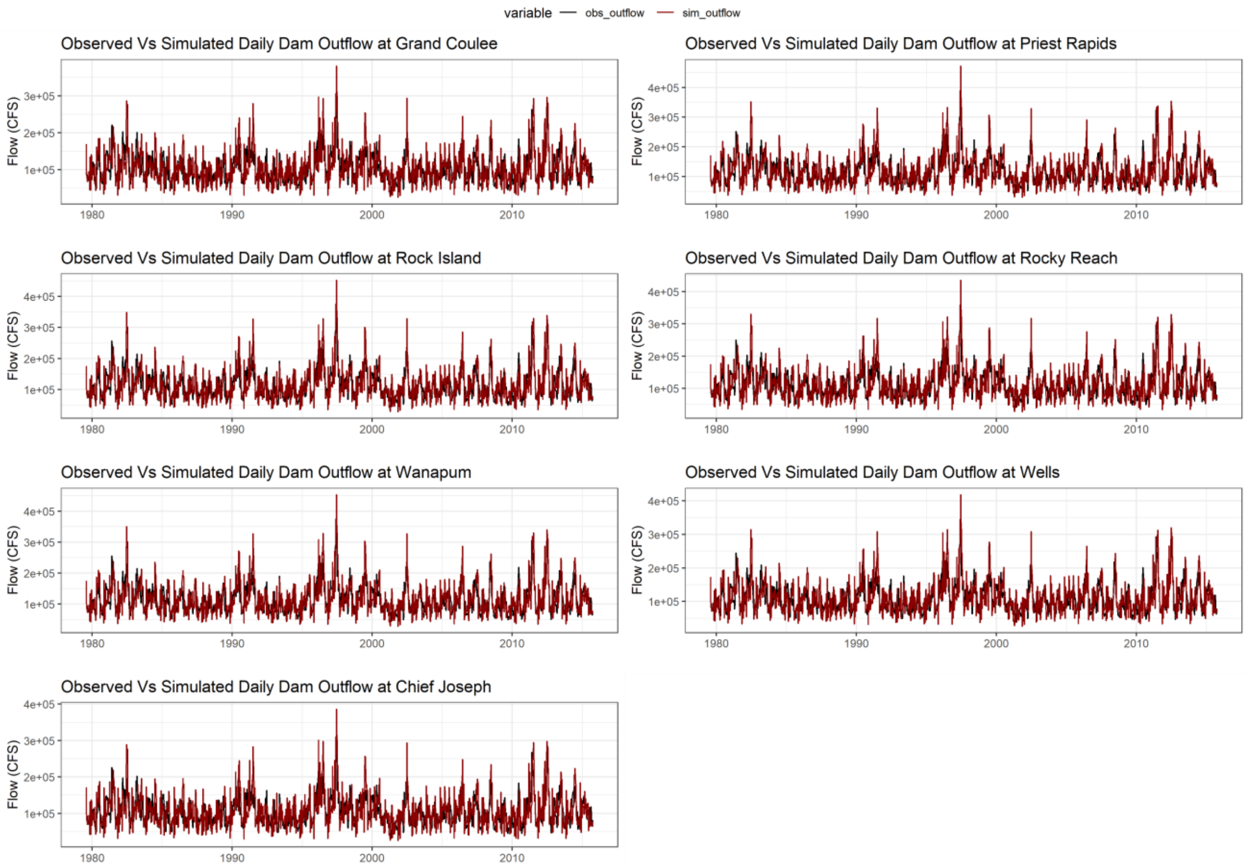

Figure 4. Observed vs. simulated weekly dam outflow from dams located in the middle Columbia region

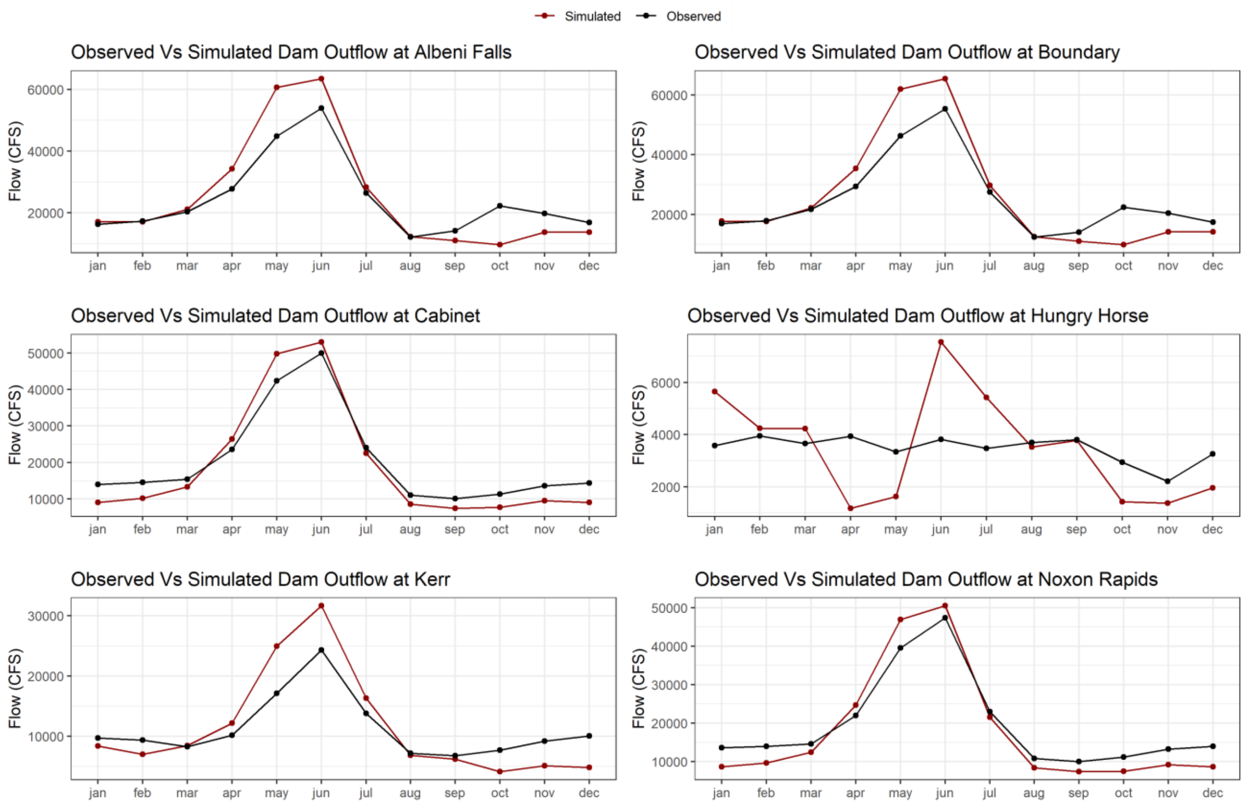

Figure 5. Observed vs. simulated mean monthly dam outflow from dams located in the Pend Oreille River.

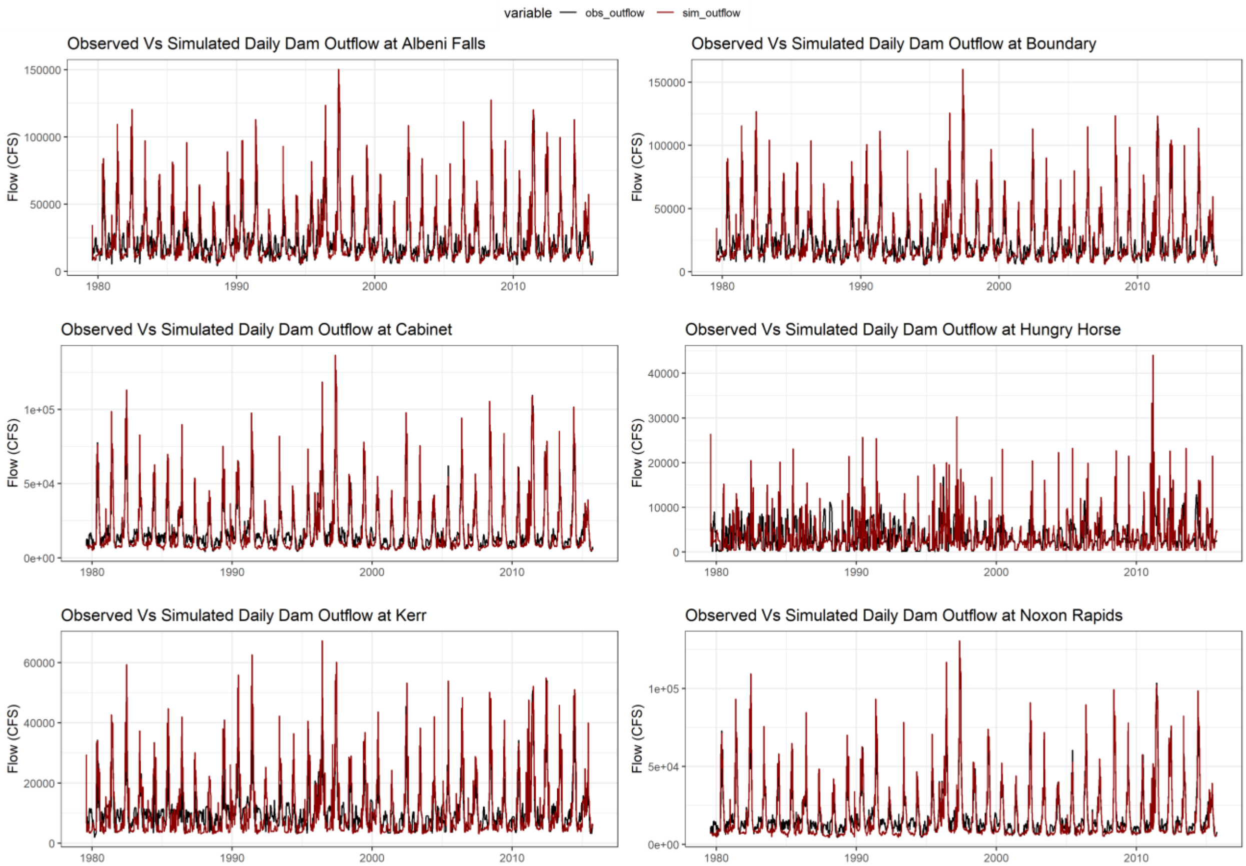

Figure 6. Observed vs. simulated weekly dam outflow from dams located in the Pend Oreille River.

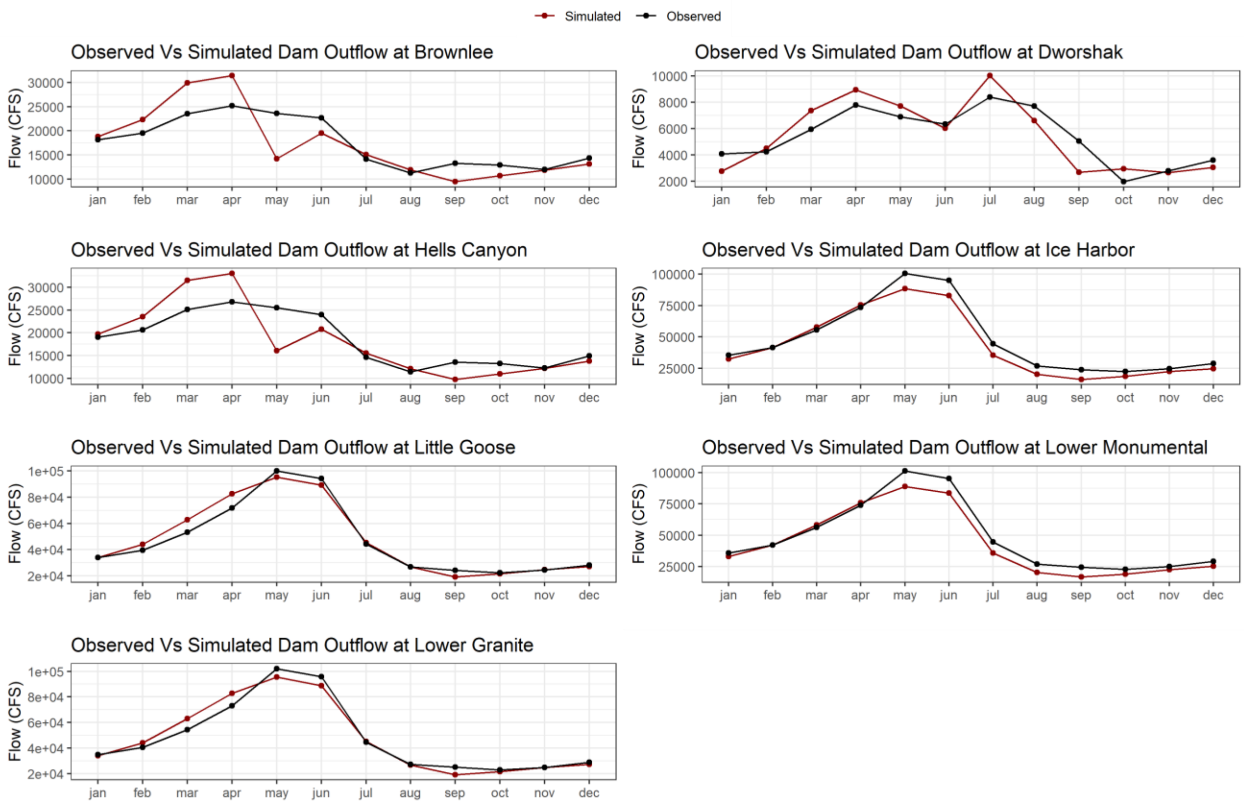

Figure 7. Observed vs. simulated mean monthly dam outflow from dams located in the Snake River sub-basin.

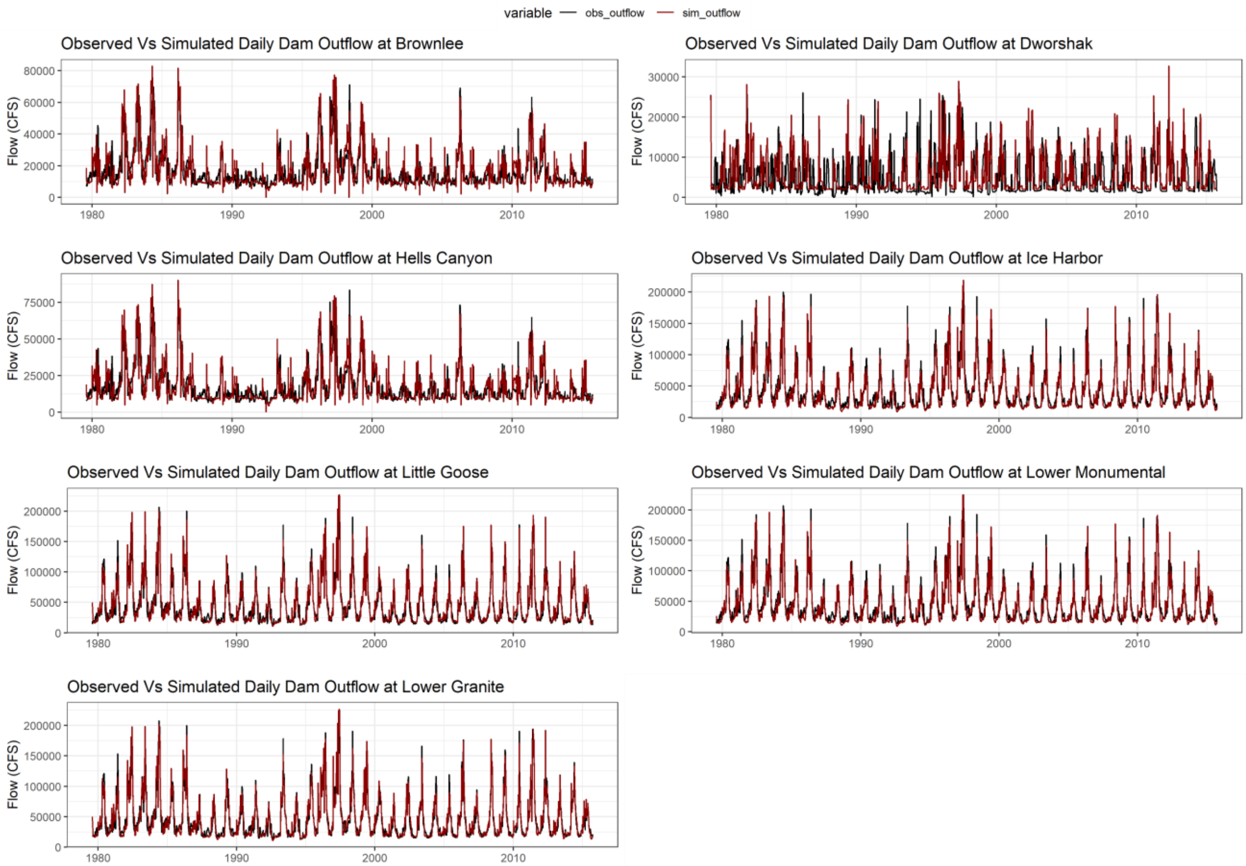

Figure 8. Observed vs. simulated weekly dam outflow from dams located in the Snake River sub-basin.

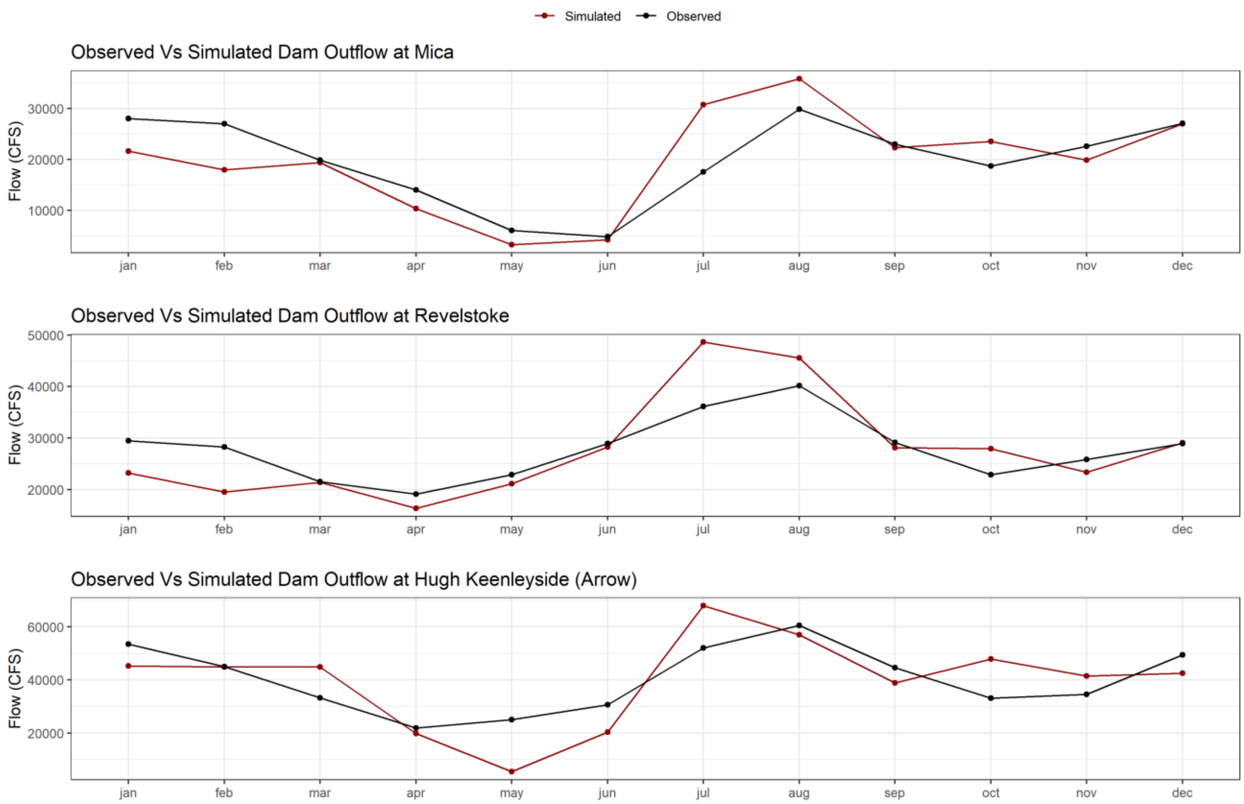

Figure 9. Observed vs. simulated mean monthly dam outflow from dams located in the Upper Columbia River region.

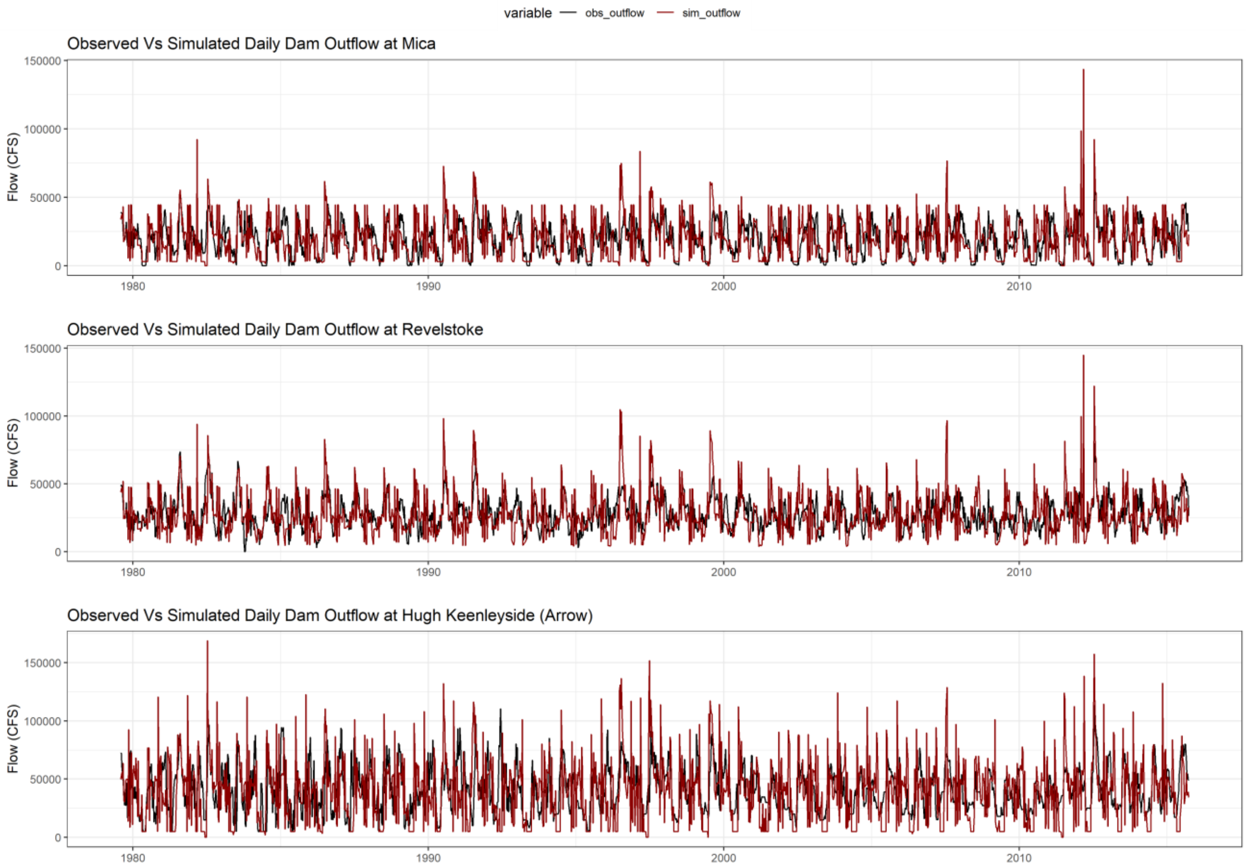

Figure 10. Observed vs. simulated weekly dam outflow from dams located in the Upper Columbia River region.

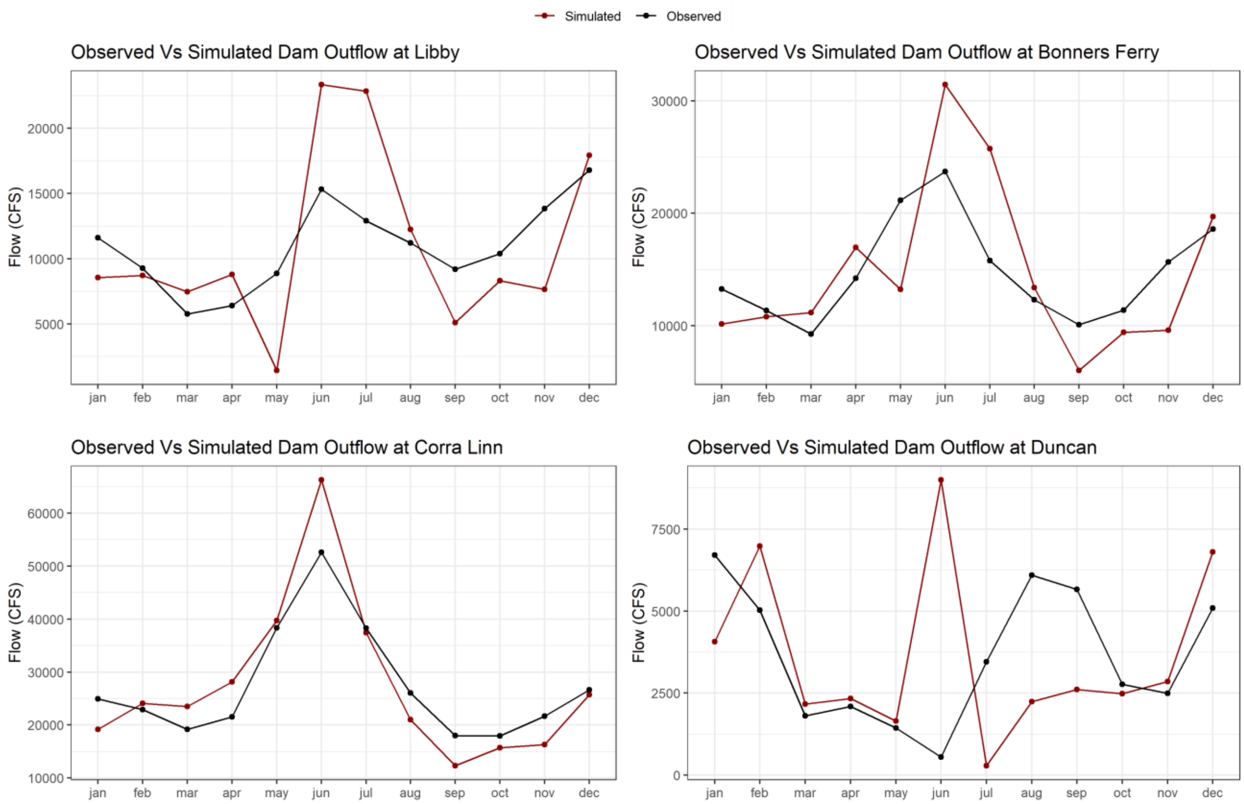

Figure 11. Observed vs. simulated mean monthly dam outflow from dams located in the Kootenay River region.

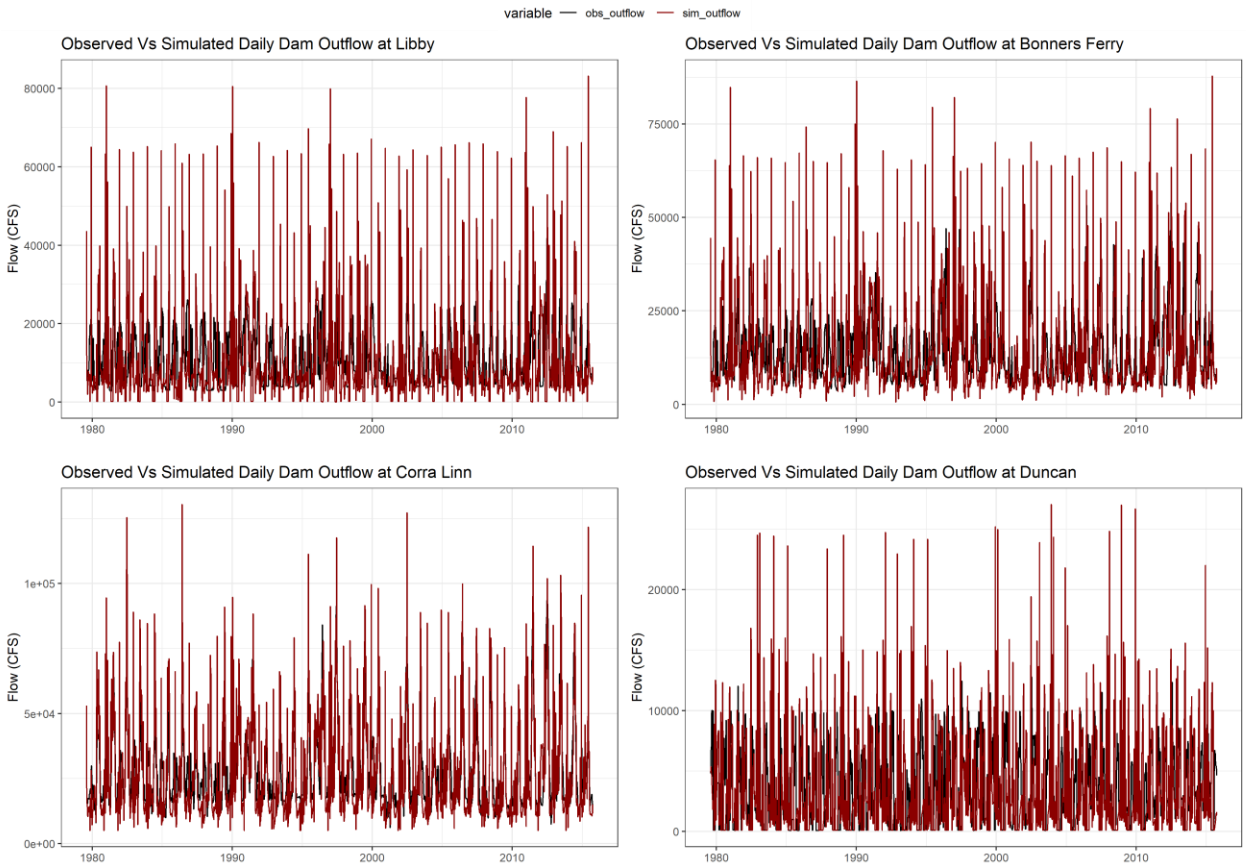

Figure 12. Observed vs. simulated weekly dam outflow from dams located in the Kootenay River region.

Table 1. Performance metrics for RColSim simulated vs. observed dam outflow. These metrics include the Pearson Correlation Coefficient (r), Mean Error (ME), Kling-Gupta Efficiency (KGE), Normalized Root Mean Square of Error (NRMSE), and Volumetric Efficiency (VE). The simulation period is from August 1979 to September 2015 and simulation time-step is weekly. The table also provides information about dam location in the basin and acronyms used in RColSim to refer to each dam.

Dame Name	Sub-Basin	RColSim Acronym	ME (CFS)	NRMSE (%)	r [-]	KGE [-]	VE [-]
Bonneville	Lower-Columbia	BON	-3626.06	39	0.87	0.86	0.83
The Dalles	Lower-Columbia	DA	-3672.65	38.8	0.87	0.86	0.83
John Day	Lower-Columbia	JD	-3483.67	39.1	0.87	0.86	0.82
McNary	Lower-Columbia	MCN	-3376.39	39.1	0.87	0.86	0.82
Libby	Kootenay	LB	17.56	131	0.28	-0.13	0.2
Bonners Ferry	Kootenay	BONF	21.06	108.7	0.38	0.11	0.4
Corra Linn	Kootenay	CL	31.37	66.5	0.73	0.47	0.64
Duncan	Kootenay	DU	1.55	140.6	0.02	-0.07	-0.04
Brownlee	Snake River	BR	-221.95	54.1	0.79	0.77	0.7
Dworshak	Snake River	DW	34.21	97.2	0.43	0.43	0.36
Hells Canyon	Snake River	HC	-223.33	51.5	0.81	0.79	0.72
Ice Harbor	Snake River	IH	-4757.39	27.8	0.97	0.89	0.84
Little Goose	Snake River	LIG	704.47	25.6	0.96	0.95	0.84
Lower Monumental	Snake River	LM	-4759.97	27.4	0.97	0.89	0.84
Lower Granite	Snake River	LG	-120.24	25.3	0.96	0.96	0.85
Grand Coulee	Mid-Columbia	GC	870.23	75.2	0.6	0.53	0.73
Priest Rapids	Mid-Columbia	PR	1055.53	61.6	0.72	0.65	0.76
Rock Island	Mid-Columbia	RI	1071.41	63.3	0.7	0.63	0.75
Rocky Reach	Mid-Columbia	RR	1031.71	66.6	0.68	0.61	0.75
Wanapum	Mid-Columbia	WA	1079.76	63.4	0.7	0.63	0.75
Wells	Mid-Columbia	WE	1026	67.9	0.66	0.6	0.74
Chief Joseph	Mid-Columbia	CJ	879.03	74.9	0.6	0.53	0.73
Albeni Falls	Pend Oreille	AF	825.71	52.1	0.9	0.68	0.72
Boundary	Pend Oreille	BD	813.61	50.6	0.91	0.69	0.73
Cabinet	Pend Oreille	CB	-1487.54	34	0.96	0.79	0.78
Hungry Horse	Pend Oreille	HH	20.09	143.9	0.16	0	0.19
Kerr	Pend Oreille	KE	183.92	75.7	0.8	0.53	0.59
Noxon Rapids	Pend Oreille	NOX	-1491.77	36	0.96	0.78	0.77
Mica	Upper-Columbia	MI	-106.95	93.2	0.43	0.37	0.46
Revelstoke	Upper-Columbia	REV	23.86	103	0.43	0.27	0.61
Hugh Keenleyside (Arrow)	Upper-Columbia	AR	-652.88	109.9	0.37	0.22	0.49

References

Gupta, H.V., Kling, H., Yilmaz, K.K., Martinez, G.F., 2009. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. Journal of Hydrology 377, 80–91. https://doi.org/10.1016/j.jhydrol.2009.08.003

Hamlet, A.F., Lettenmaier, D.P., 1999. Effects of Climate Change on Hydrology and Water Resources in the Columbia River Basin1. JAWRA Journal of the American Water Resources Association 35, 1597–1623. https://doi.org/10.1111/j.1752-1688.1999.tb04240.x

Kling, H., Fuchs, M., Paulin, M., 2012. Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. Journal of Hydrology 424–425, 264–277. https://doi.org/10.1016/j.jhydrol.2012.01.011