RColSim: An Open-Source Regional Water Management Model for the Columbia River Basin

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Abstract

The Columbia River water management system is an example of an institutionally-complex human–environmental system that is used to balance the conflicting demands of its food–energy–water (FEW) stakeholders. The system includes more than 30 major storage and run-of-the-river dams that are operated to control floods, produce hydroelectricity, meet irrigation demands, and support environmental flow targets. While FEW stakeholders in the system are already experiencing significant stressors (e.g., droughts, floods, ecosystem impacts), the system is projected to be more vulnerable due to changes in climate while facing potential evolving water management policies (e.g., the transboundary U.S.–Canada Columbia River Treaty). The research community has extensively studied the future of the system using the original version of ColSim (written in Stella); however, to date, the absence of an open-source river-system modeling tool that can efficiently simulate system dynamics for a large ensemble of climate and/or management scenarios has been a limiting technical challenge. In this study, we present RColSim, a script-based river-system model of the Columbia River written in the R programming language. The model considers rule curves and regional constraints to simulate the operation of 33 dams on the Columbia River and also takes system-wide environmental and hydroelectricity targets into account.

Statement of Need

The Columbia River Basin (CRB) is the largest supplier of hydropower in the Unites States and generates more than 40% of the U.S. hydroelectric energy supply. Additionally, the agricultural sector of the region produces more than 7% of U.S. agricultural commodities in terms of economic value. The CRB's drainage basin extends to seven U.S. states and the Canadian province of British Columbia and affects many other sectors and stakeholders, such as urban water utilities, fisheries, the recreation industry, and river-based navigation. CRB dams also play a crucial role in protecting the region from flooding dangers (Jones and Hammond, 2020; Lee et al., 2006). The CRB water system carries significant cultural and spiritual importance for various societies, such as Indigenous residents of the region in both the United States and Canada (Hand et al., 2018; Wicks-Arshack et al., 2018).

The underlying algorithms used in RColSim were originally coded in a monthly time-step, Stella-based system-dynamics model called ColSim, which was used in a number of different studies to explore climate change impacts on the integrated system (Hamlet and Lettenmaier 1999; Miles et al. 2000), the economic value of long-lead climate forecasts (Hamlet et al. 2002), flood control optimization (Lee et al. 2006), Pacific Northwest energy impacts (Hamlet et al. 2010), and agriculture production (Rajagopalan et al. 2018). Despite wide application of the code, Stella is not a freely available programming platform, and due to the limitations of the coding environment, the original model could not be scripted to run efficiently in ensemble mode, and was not compatible with studies requiring high-performance parallel computing.

The Columbia River system is expected to undergo various types of stressors in the future, including land-use change, climate change, increasing hydrometeorological extremes, and revision of the transboundary agreement between the United States and Canada (Cosens, 2010; Islam et al., 2016; Krutilla, 2018; Rajagopalan. et al., 2018; Rupp et al., 2017). To explore the ramifications of these transformations, a myriad of scientific papers and projects have focused on the CRB during the last three decades. However, a comprehensive investigation of the impacts of these stressors often necessitates carrying out intensive computational experiments to conduct optimization, sensitivity analysis, and bottom-up assessment. These experiments allow us to investigate system behavior and best management practices under unknown future climatic and socioeconomic uncertainties and stressors (Herman et al., 2013; Marchau et al., 2019; Moallemi et al., 2020; Quinn et al., 2020).

Currently, the authors are not aware of any open-source script-based water-management models of the region that can be deployed on computer clusters for tens of thousands of simulations; the simulation tools used to represent the infrastructural and institutional details of the Columbia River have been either overly simplistic or non-open-source. RColSim responds to these diverse needs and provides a script-based open-source model that can be used in future studies that aim to improve planning and management of water resources in the CRB under deep uncertainty.

Model Description

ColSim and RColSim follow the reservoir rule curves that are used to guide system operation in the real world. These rule curves include the upper flood-protection rule curve (the dam stage cannot go higher than this level), the lower-limit operating rule curve (the dam stage cannot go below this level), the assured- and variable-refile rule curves (the assured or fixed rule curve is based on an analysis of historical records and is unaffected a specific year's projected hydrological conditions, while the variable rule curve is responsive to each year's projected water supply conditions), and the critical rule curves (guides reservoir operation for hydropower generation during low flow years). Each week, system operators select a rule curve on the basis of the season (Figure 2), projection of water availability during that season, and flood-control projections; RColSim closely follows this operation logic. Additionally, we have modified several aspects of the code in RColSim. For example, unlike the original ColSim model, irrigation demands in RColSim are provided as a dynamic variable that changes every week. Several past and ongoing projects have used the VIC-CropSyst model to simulate irrigation requirements. We have also improved RColSim simulations compared to the original model by updating the rule curves of Canadian dams (i.e., Mica, Arrow, and Duncan), which are the largest storage facilities in the system. Therefore, RColSim takes advantage of the original widely used conceptual algorithms used in ColSim while using the freeware and data-processing features of the R programming language.

RColSim simulates the operation of more than 30 storage and run-of-river reservoirs in the Columbia River system using a weekly time step. The purpose of the model is to capture the operations and streamflow effects on each dam, which jointly reduce flood risk while meeting agricultural, energy production, and environmental demands in the system. The model is able to simulate the system-wide constraints imposed by the Columbia River Treaty between the United States and Canada. In other words, each reservoir in the system simultaneously handles its dam-specific operation goals (e.g. minimum flows, and rule curve operations) while contributing to system-wide flood protection, energy production, and support for environmental flows. RColSim simulates six main tributaries and dam systems of the CRB: the upper, middle, and lower Columbia basins; Kootenay River Basin; Snake River Basin; and Pend Oreille (Figure 1).

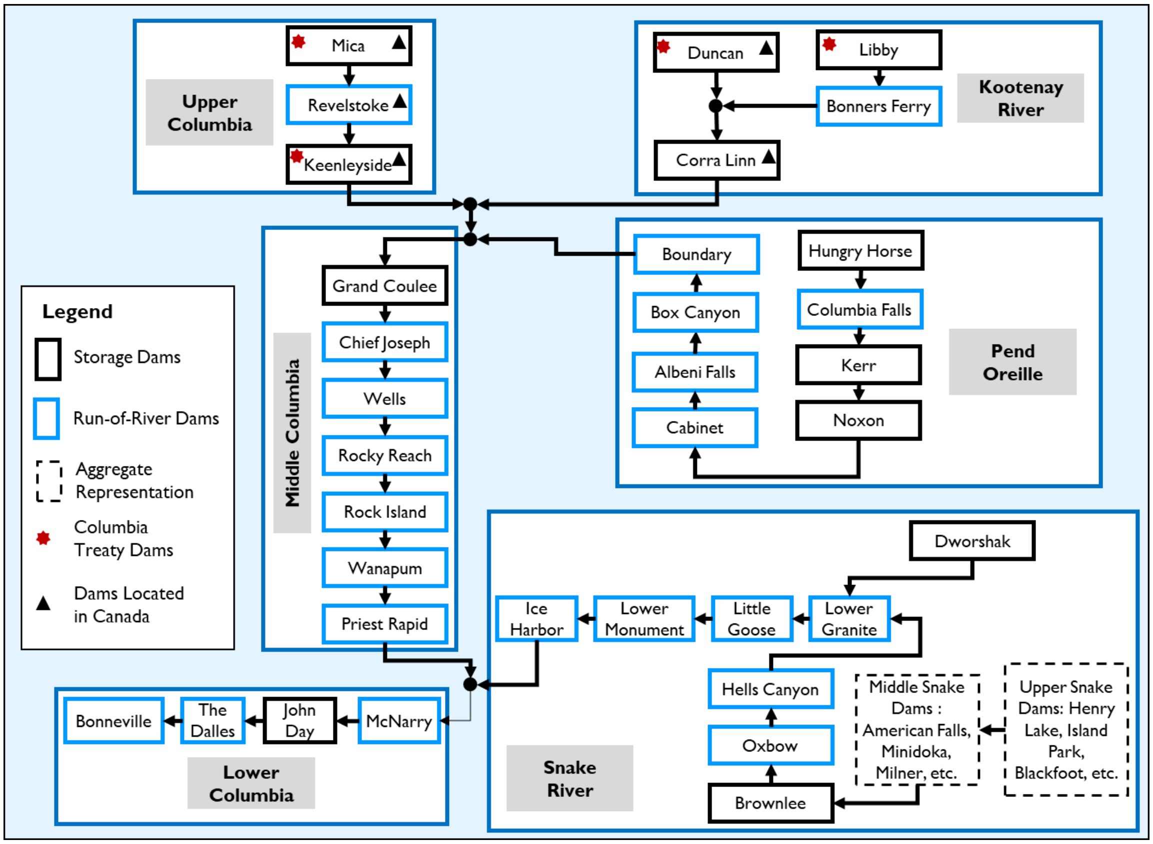

Figure 1. Conceptual schematic of RColSim and the six major sub-basins that RColSim simulates.

The model is coded in the R programming language and is designed for parallel computing on high-performance computer clusters. Therefore, the model can be used for the type of large-scale ensemble simulations that are frequently needed for exploratory analysis (Bankes, 1993) and uncertainty quantifications . Additionally, the script-based nature of the model can facilitate online connections to other hydrologic land-surface models as well as other socioeconomic system-dynamics simulation tools.

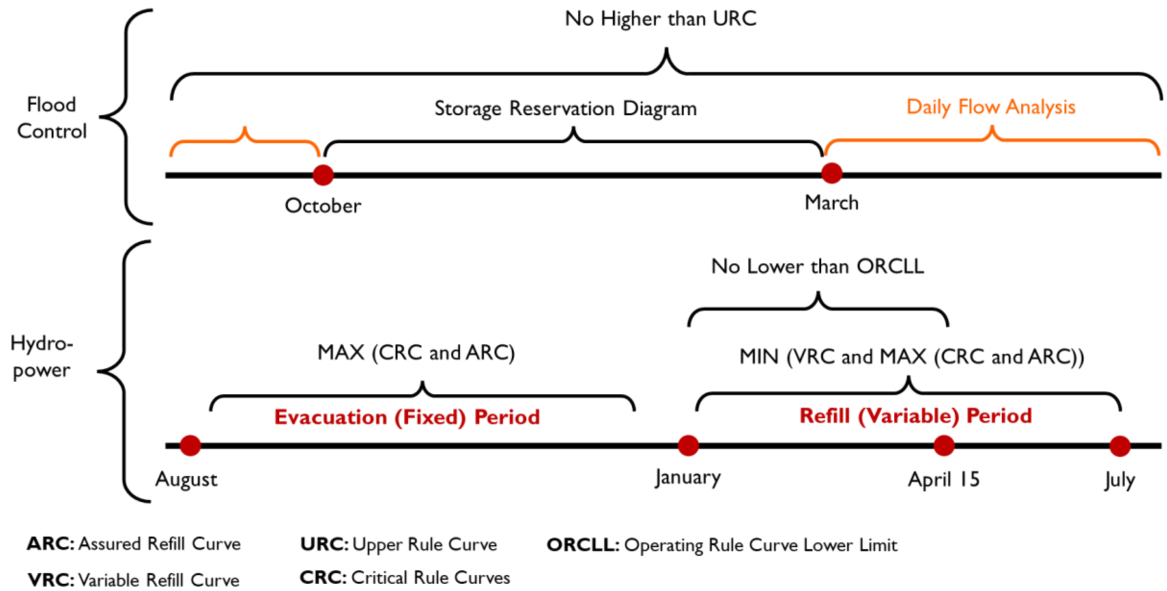

Figure 2. Seasonality of system operation and rule curve selection process for operation of the Columbia River Basin. Each week one of these rule curves is selected for the operation of each dam in the CRB water system. Overall, water stored behind dams cannot be more than the flood control URCs. In terms of the minimum operation level (CRC and ORCLL), the rule curves cannot drop below the dam water level during the worst historical water supply year.

Model Evaluation

We compared observed versus RColSim-simulated reservoir signature (defined as the difference between mean monthly streamflow with and without the reservoir effect) at various system reservoirs to assess the performance of our river-system model and show that the model can capture the overall storage dynamics of the system reasonably well (Figure 2). There are, however, discrepancies that can stem from many simplifying assumptions applied during the abstraction of the complex CRB water system. There are also model limitations associated with uncertainties in streamflow input data, irrigation and energy demands, and rule curves used in the model.

In addition, Table 1 provides a comparison between simulated and observed weekly dam outflow at the dams included in RColSim. We used the following five performance metrics to explore the performance of RColSim in the simulation of dam outflow: Pearson correlation coefficient (r), mean (relative) error (ME), Kling-Gupta efficiency (KGE; Gupta et al., 2009), normalized root mean square of error (NRMSE), and volumetric efficiency (VE). These performance metrics are thoroughly defined in Supplemental Materials.

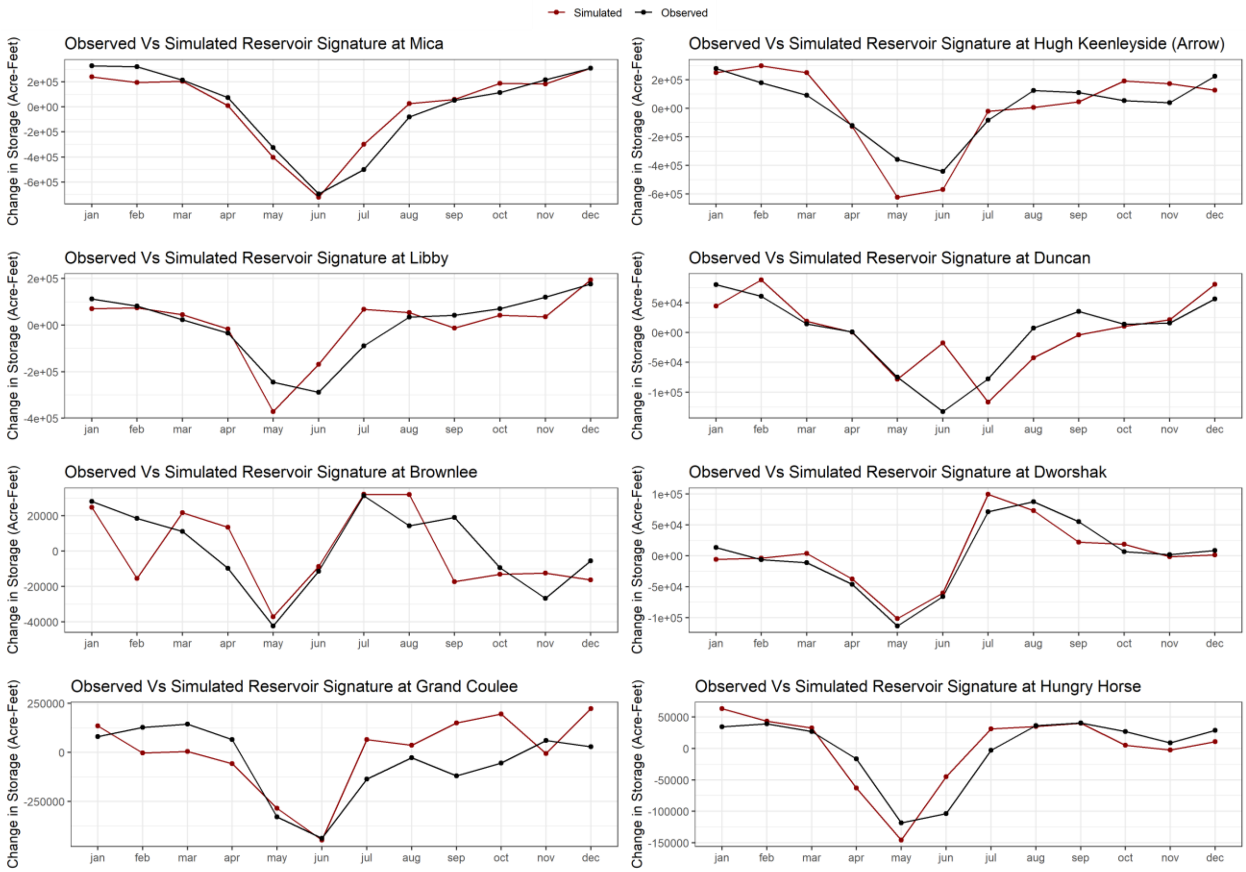

Figure 3. Simulated vs. observed long-term mean change in reservoir storage by calendar month, based on weekly time step simulation for the period 1979 to 2015.

Finally, the Supplemental Materials of this paper provides an additional comparison between observed and simulated dam outflow at all CRB dams represented in RColSim. The information about the original datasets used to conduct the RColSim simulations for this comparison can be found in the Supplemental Materials. Also, observed dam outflow dataset have been discussed in the Supplemental Materials.

Model Limitations

There are tributaries within the Columbia system that are currently excluded from RColSim because their water contribution relative to the overall annual flow at the Columbia River scale is negligible. Examples of these tributaries include the Yakima, Walla Walla, and Chelan river basins. RColSim also represents the upper and middle Snake River dams as two hypothetical integrated dams. While these dams do not significantly contribute to the overall water supply of the Columbia River, their absence limits our ability to explore research questions in those specific regions (e.g., the headwater of the Snake River). Therefore, future studies can more explicitly incorporate operational details of dams in those regions and enable RColSim to answer broader ranges of questions at the subbasin scale. While rule curves of Canadian dams have been updated, there are other dams that can benefit from bringing their operations up-to-date (e.g., Brownlee, Hungry Horse and other dams in the Pend Oreille River dam group), and it is our hope that future studies will undertake these kinds of modifications in an open-source environment.

Table 1. Performance metrics for RColSim simulated vs. observed weekly 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 August 1979 to September 2015. 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

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