Comparing Reservoir Refill for Power Generation and Flood Risk Management

Thomas Chisholm U S Army Corps of Engineers Northwestern Division Portland, OR
o2boutdoors2@yahoo.com

Weimin Li U S Army Corps of Engineers Northwestern Division Portland, OR
Weimin.Li@usace.army.mil

Abstract

Snowmelt driven reservoir systems support both flood risk management (FRM) and hydroelectric power generation objectives. Analysis used hydrologic and power system data taken from the US Pacific Northwest. Data regression showed that electricity demand increases with temperature during spring and summer, electricity price increases with demand, and increasing river flow decreases electricity price. A simple model compared refill optimized for power generation and for flood risk management. The model includes two reserviors and a total of three rivers. The comparison of refill operations showed similarities and differences. In general, refill operations that economically optimized for power generation had more variability because electricity price has many drivers including demand, transmission availability, and supply from non-hydrogeneration fuels including natural gas and wind.

Introduction

Dams and their reservoirs usually have multiple purposes. Common purposes include hydropower, flood risk management, irrigation, water supply, navigation, recreation, and ecological function. (U S Army 2017) Project operations aimed at fulfilling one purpose may not be ideal for other purposes and may even adversely impact them. The best operations for a particular purpose depend on the environment a project resides in. In many regions water supply varies with season. (Penn 2001) Some areas have wet and dry seasons. If the wet season occurs during a cold season, precipitation can collect as snow, then be released relatively suddenly in the spring.

Hydropower objectives prefer to keep reservoirs as full as possible because more full reservoirs provide higher head for generators, which allows a given volume of water to yield more electricity when it is released through turbines (Caldwell 2019). Operation of power systems gives great importance to reliability, also called “keeping the lights on”. Hydro generation will draft reservoirs to support reliability. Electricity generation from any fuel is primarily an economic activity with value of electricity varying. Even if keeping reservoirs full yields more total power, drafting during periods of high electricity prices may produce a more economically desirable operation.

Flood risk management objectives prefer to keep reservoirs empty and fill them only when avoiding floods requires reducing flows. Although a few reservoirs implement this approach it is uncommon in projects with multiple objectives because it conflicts with pretty much all other reservoir purposes. Therefore, reservoirs stay as full as possible and draft as needed to provide flood risk management benefits. Drafting for flood risk management purposes is often timed so that it provides value through other project uses. For example, drafting may occur when electricity prices are high or when fish benefit from higher instream flows.

Data

This analysis investigates a basin with snow melt driven hydrology. In such systems snowpacks build during the cold season then melt when the weather warms. In general, temperature decreases with latitude and elevation. Mountains foster orographic precipitation so may be more effective at accumulating snow. A region with snowmelt driven hydrology but also significant population centers is the United States Pacific Northwest and southwestern Canada.

Analysis uses a system (Figure 7) loosely based on the United States Pacific Northwest. Inflow comes from 3 rivers. The inflow from each river averages 3000 cubic feet per second (cfs) over a year but has its hydrologic shape taken from a stream gage. Data sources include the following stream gages: Environment Canada 08NJ013 Slocan River near Crescent Valley (River 1), USGS 12449950 Methow River near Paternos, WA (River 2), and USGS 13333000 Grande Ronde River at Troy, OR (River 3) for the period from 2001 – 2021. All 3 rivers are mostly unregulated. None of them experience exceptionally large irrigation withdrawals. Data was scaled to produce data streams with each river's shape and average flow of 3000 cfs over the period of record. Figure 1 shows flow for a portion of the period of record. River 1 (Slocan shape) is the most northerly and River 3 (Grande Ronde shape) is the most southerly. As expected, the freshet for River 1 arrives last and River 3 first. River 2 often has the largest peak flows although in some years River 1 has larger peaks. River 1 has a lake upstream of the gaging point that may attenuate peak flows. River 3 is more southerly so more driven by rainfall than snowmelt, which reduces peaks.

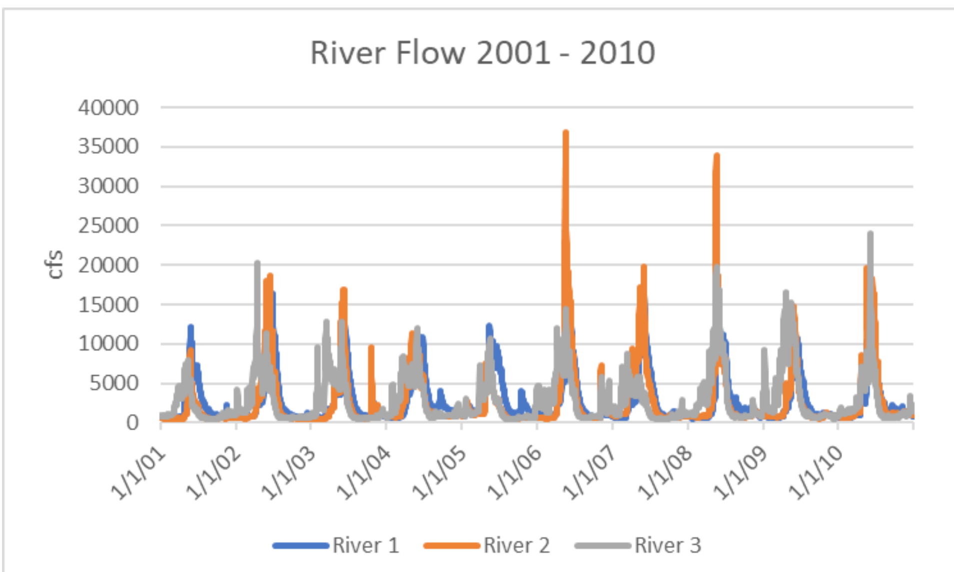

Figure 1 Scaled flow in the three rivers used in data analysis and modeling. Although data from 2001-2021 was used in analysis the figure only shows 10 years of data to enhance clarity.

Other data of interest includes electricity prices, loads, and temperature. Electricity trades in blocks for varying lengths of time and various times before delivery. Price data came from the Energy Information Administration (EIA) Web Site (https://www.eia.gov/electricity/wholesale/) The primary trading hub in the U S Pacific Northwest and closest to the rivers providing flow data is called Mid-C, whose location is several substations south of Grand Coulee Dam. Electricity trades with delivery dates from months to minutes before it is used. This study used day ahead data. The period of delivery is usually either 6 am to 10 pm or 10 pm to 6 am with the former referred to a heavy load hours and the latter as light load hours. Electricity usage is usually greater during daytime, when most people are doing energy-intensive activities, than at nighttime when most people are sleeping. This analysis used heavy load data. Data for some days was not available from the EIA dataset so missing data was calculated using interpolation. Usually, electricity demand is lower during weekends and holidays when many businesses are not operating. All day Sunday is considered light load hours. Calculation of missing load data did not consider day of week.

Electricity demand is calculated for balancing authority control areas. There are over a dozen of these in the US Pacific Northwest. The largest and most geographically diverse is maintained by the Bonneville Power Administration, making it a good surrogate for regional electricity demand. Data for it is available back to 2007 at
https://transmission.bpa.gov/Business/Operations/Wind/

Snow melts when temperature exceeds its melting point and melts more rapidly with higher temperature. A representative temperature location is Spokane, WA because it is centrally located among the three rivers whose discharge shape was used in the analysis. Daily average temperatures were obtained from the National Climatic Data Center
https://www.ncei.noaa.gov/cdo-web/ station GHCND:USC00457941

Table 1 shows correlations between data series. Correlations for each year were calculated separately because variations between years would lead to unrealistically low correlation. For example, there is annual variation in power prices mostly driven by worldwide natural gas market variability. The correlation period was between 16 April and 15 July. Some years have early snow melt, and some years have later snow melt, which impacts results. Rain events for almost all years positively correlate with higher flows. The correlation is weak because there is a delay in precipitation entering streams and much of the flow comes from melting snow that fell as precipitation many days or months previously. Flow and temperature weakly correlate. While higher temperatures cause snow melt and higher flow, higher temperatures also occur in later season when flows are low, particularly in years with early runoff. Price negatively correlates with flow in one of the stronger correlations investigated. During periods of high flow in areas that rely on hydrogeneration electricity prices decrease as supply increases. Price and load also correlate strongly. As demand for electricity increases price also increases. The data confirm the economic principles relating supply and demand. Electricity demand relates to temperature because electricity is used for both heating in cold weather and air conditioning in warm weather. Because electricity usage increases during both hot and cold weather with minimum usage at an in between temperature the relationship is not linear, which decreases the linear correlation coefficient.

Table 1 Yearly correlation coefficients between data series by year. Data is from 16 April to 15 July.

year	flow precip	flow temp	price flow	price load	load temp
2001	0.09	-0.04	0.23		
2002	0.00	0.34	-0.42		
2003	0.18	0.19	-0.25		
2004	0.21	-0.28	-0.22		
2005	0.22	-0.17	-0.63		
2006	0.29	0.09	-0.21		
2007	0.27	-0.17	-0.15	0.40	0.58
2008	0.20	0.28	-0.53	0.09	0.03
2009	-0.08	0.04	-0.35	-0.16	-0.02
2010	0.23	0.13	-0.78	0.25	-0.07
2011	-0.08	0.50	-0.48	0.57	-0.42
2012	0.11	-0.03	-0.36	0.38	0.27
2013	0.13	0.11	-0.04	0.54	0.03
2014	-0.15	-0.03	-0.28	0.47	0.51
2015	0.17	-0.20	-0.46	0.63	0.53
2016	0.00	-0.25	-0.63	0.47	0.39
2017	-0.03	-0.05	-0.21	0.46	0.45
2018	0.20	0.04	-0.58	0.58	0.14
2019	0.22	-0.21	-0.61	0.50	0.32
2020	0.32	-0.03	-0.47	0.09	0.41
2021	0.06	-0.40	-0.21	0.53	0.76
average	0.12	-0.01	-0.36	0.39	0.26
std dev	0.13	0.22	0.23	0.22	0.31

Figures 2-6 below show xy plots of data from 16 April to 15 July for the year 2021. In Figure 2 price decreased with increasing flow as it did in all other years except 2001. Because 2021 had low water supply and data shows daytime not nighttime power prices, there were not days with negative power prices, which can happen if supply exceeds demand. The year 2001 was very dry and experienced an unusual electricity market in the western US. Several days had notably high prices, which occur occasionally and are often loosely related to either weather or water supply. Discussing market anomalies is beyond the scope of this paper. In 2021 the spring did not have many days with precipitation resulting in a low correlation as shown in Figure 3. Figure 4 shows flow decreased with temperature. The year 2021 experienced early snow melt resulting in extended period in late June and July with low flow and high temperatures. Figures 5 and 6 show typical relationships of prices increasing with demand and price decreasing with electricity demand.

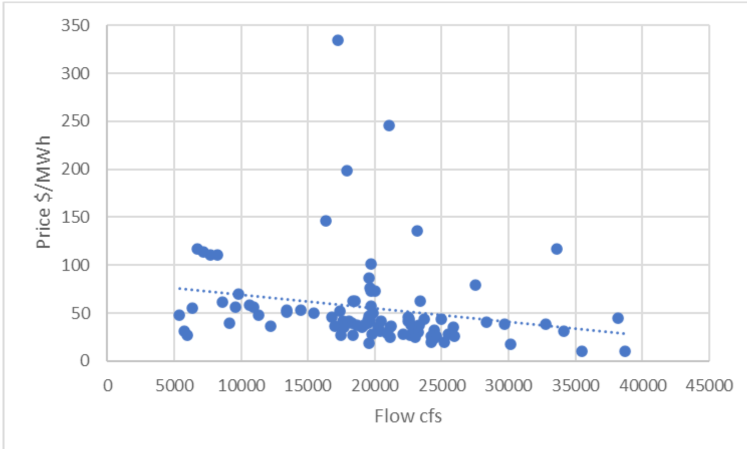

Figure 2 Scatter plot and regression of 2021 Heavy Load Hour Mid-C price in dollars per MWh and sum of flow of the 3 Rivers in cfs for 16 April to 15 July

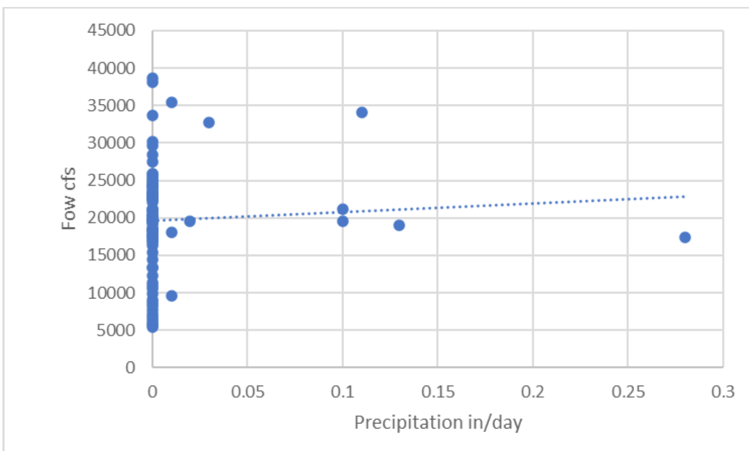

Figure 3 Scatter plot and regression of 2021 sum of the three rivers flow in cfs and precipitation in in/day at Spokane, WA for 16 April to 15 July

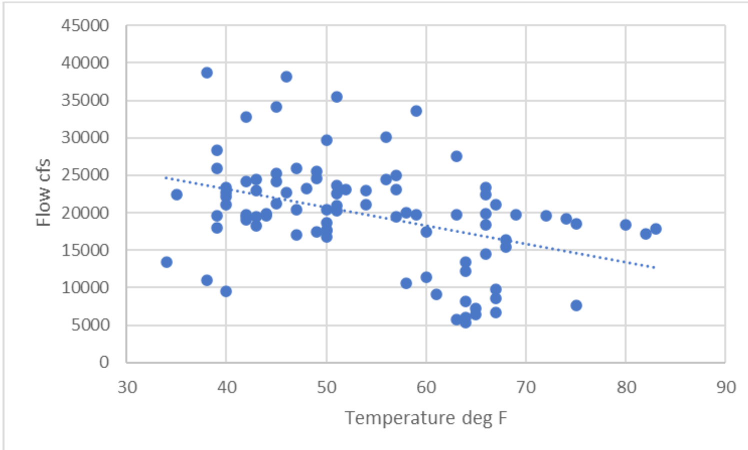

Figure 4 Scatter plot and regression of 2021 sum of the three rivers flow in cfs and day average temperature in degrees F at Spokane, WA for 16 April to 15 July

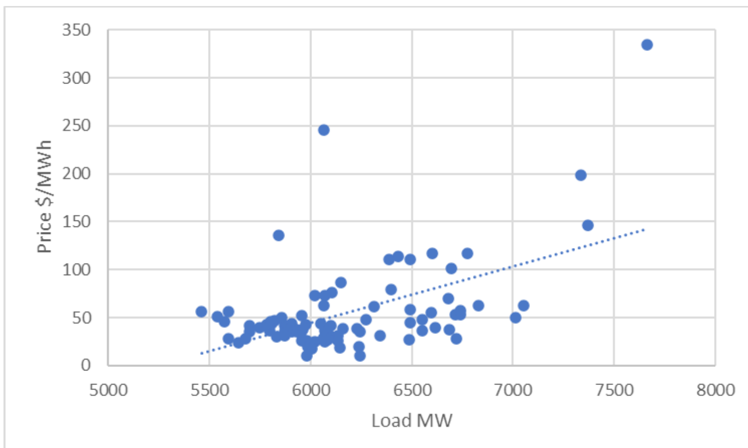

Figure 5 Scatter plot and regression of 2021 Heavy Load Hour Mid-C price in dollars per MWh and Bonneville Power Administration control area load in aMW for 16 April to 15 July

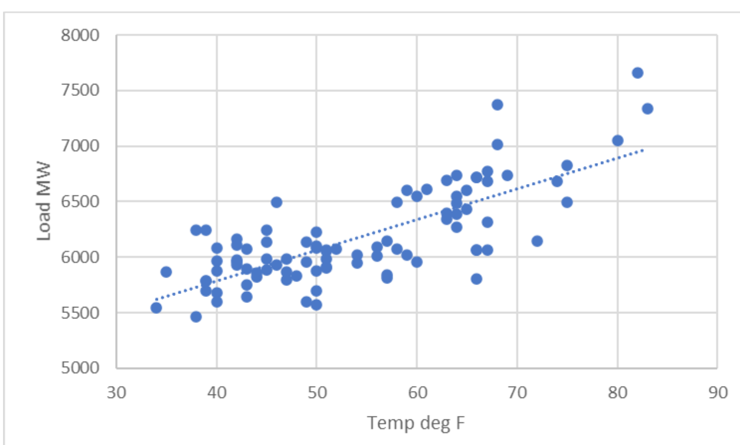

Figure 6 Scatter plot and regression of 2021 Bonneville Power Administration control area load in aMW and day average temperature in degrees F at Spokane, WA for 16 April to 15 July

Modeling

The simplified system shown in Figure 7 is used for analysis. The two reservoirs have capacities of 100 thousand cubic foot per second – day (ksfd). All three rivers have average annual discharge of 3000 cfs.

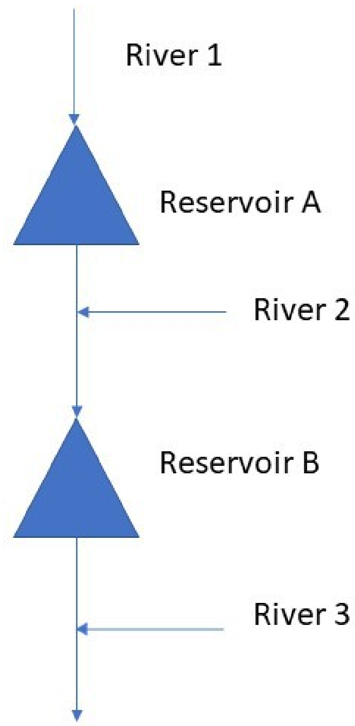

Figure 7 A schematic of the system used to investigate and compare refill strategies.

Flood risk management typically tries to minimize peak flows. To do this all flow above a control flow is stored. A balance between inflow and available storage determines the control flow. This analysis assumed perfect foresight whereas in actual operations storage volume is preserved to allow for uncertainty in projected inflows.

Power operations prefer to store water when prices are lower. However, there is feedback between hydrogeneration production and prices as illustrated in Figure 2. If operators excessively reduce discharge, electricity could be in short supply causing prices to rise. Power operations were modeled with a minimum flow and target price. If prices are above the target price, no water is stored. If prices are below the target price, the fraction of inflow discharged is the ratio of the historical Mid-C price and the target price. A minimum discharge of 1000 cfs is enforced. Because modeling extends over the refill season, drafting does not occur, although in actual operations drafting would occur if needed for reliability.

Control flows and target price, respectively were calculated using a root-finding approach that solved for the control flow and target price such that the reservoir started with 0 ksfd content and ended with reservoirs full at 100 ksfd. Analysis assumed future flows and prices were known exactly. In real time, operations would be forecast and allowance made for forecast uncertainty.

Results

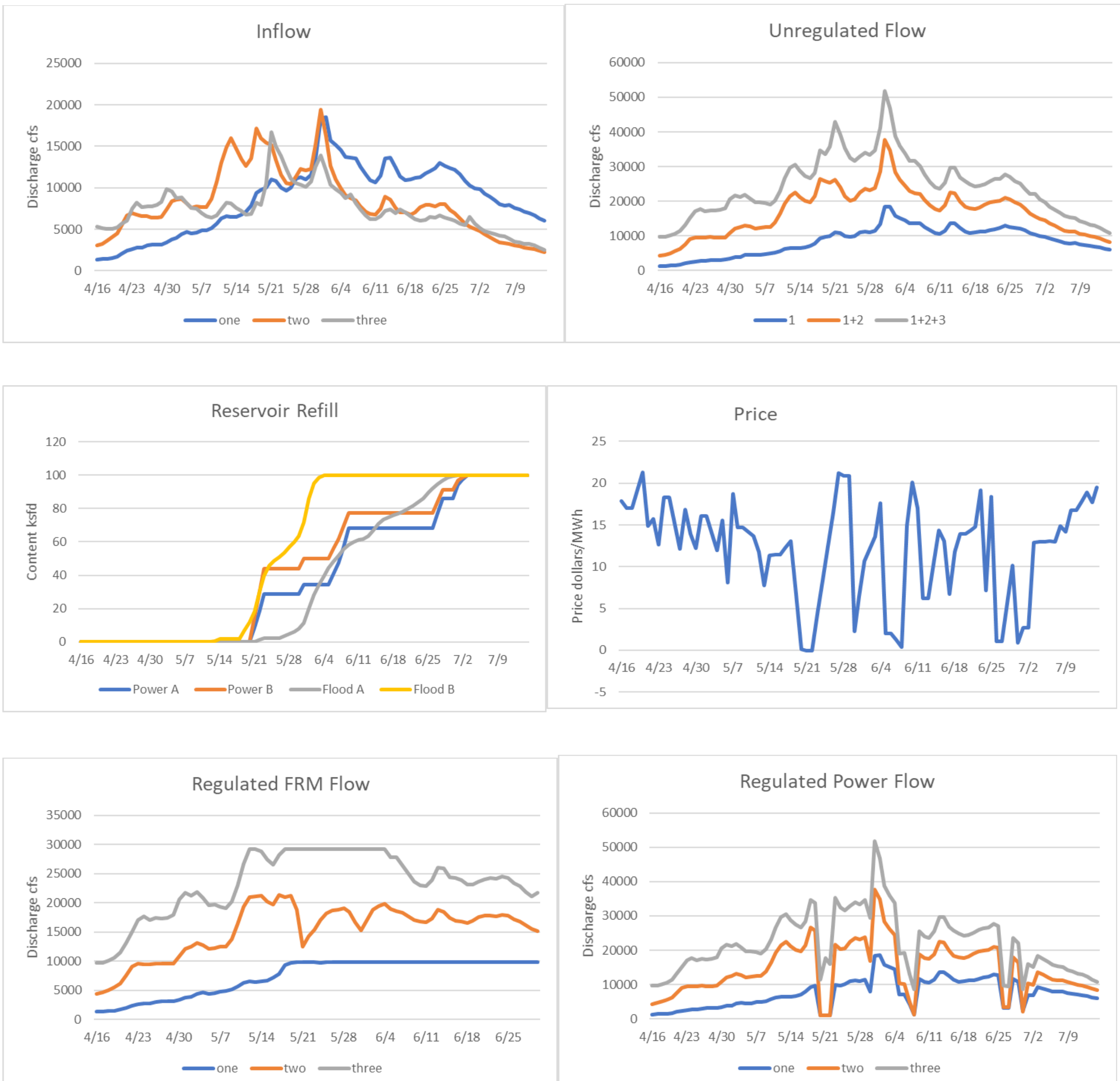

Figure 8 The plots above show model output. The plots in the top row are a and b, the second-row c and d, and the bottom row e and f.

The plots above show model data and results for the 2020 refill season. At the start of the period of interest River Three has the highest flows and at the end of the time series River One has the highest flow (Figure 8a). This is consistent with River One being the most northerly location and River Three being the most southerly. Despite this all three rivers peaked about 1 June. This was driven by both high temperature and rain. Spokane, Washington had a high of 89 F on 30 May followed by .71 inches of rain on 31 May.

As Figure 8c shows Mid C electricity prices vary greatly and appear to be somewhat erratic. This is not unexpected as described in the discussion in the Data section of this paper. Figure 8e shows that control flow driven FRM operations provide constant outflows where the control flow governs discharge when inflow exceeds the control flow. Discharges equals inflow at other times. Power operations shown in Figure 8e reduce discharge when prices are low and maintain discharges close to inflow when prices are high. Variable prices lead to variable discharges throughout the refill season.

The period close to 1 June illustrates a difference because high temperature led to high natural inflow. The FRM operation reduced discharges. The high temperatures also lead to increased electrical demand for air conditioning load and thus higher prices. The power operation thus did not store water. It is noted that the power model does not consider turbine capacity. If inflows exceed the ability of projects to use water to generate electricity, it becomes economically beneficial to store water, even if prices are high, and release the water when it can generate electricity.

Refill curves show an operation where Reservoir A attempts to limit its peak discharge and Reservoir B attempts to limit the sum of its discharge and River Three flow. Reservoir A could also operate to limit the sum of Reservoir B discharge and River Three flow. Reservoirs typically can operate for local FRM, as Reservoir A is doing, or system FRM as Reservoir B is doing. Choosing between the two options depends on FRM needs of the watershed.

In the FRM refill operation Reservoir B fills rapidly during the peak. Reservoir A fills more slowly because it has more space relative to the smaller River One inflow. Both reservoir's power operations respond to the same price signal so fill in a similar manner. The daily changes in price leads to daily changes in fill rate.

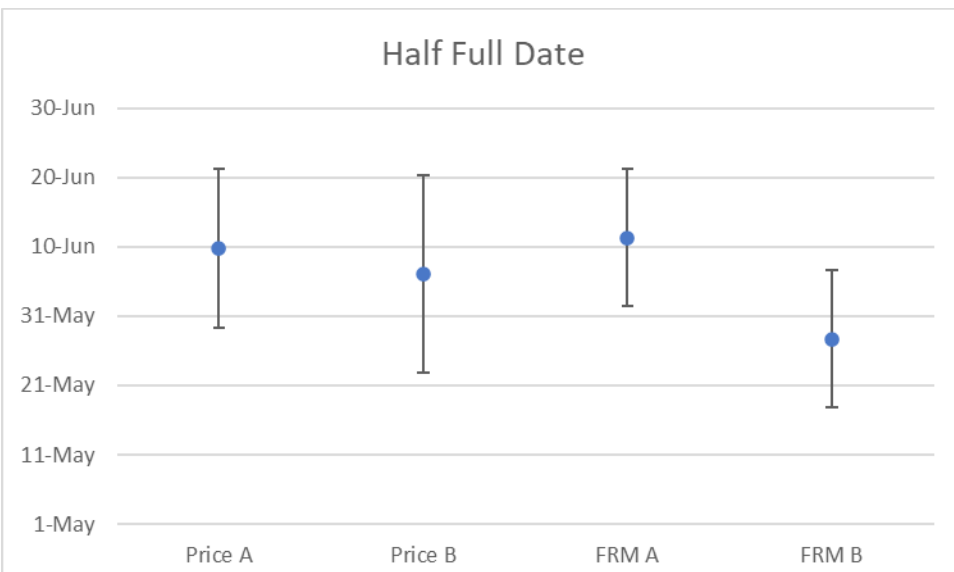

Figure 9 Mean date or Reservoirs A and B with FRM and Power objectives reaching 50 ksfd or half full. The error bars indicate one standard deviation either side of the mean.

The model ran for the 21 years from 2001 to 2021. Figure 9 shows results from the runs. Reservoir A filled later because River 1 experienced peak flow later. When prices drive refill there is more variation in refill timing. Operations of reservoirs A and B are more similar when both are driven by the same price signal.

Conclusion

This paper explored relationships between drivers of water supply available for hydrogeneration and electricity prices. Data show expected relationships. During spring and summer electricity demand increases when higher temperatures increase air conditioning power demand. When demand increases prices also increase. When high flows lead to increased power generation prices decrease. A modeling effort investigated refill in an artificial system with scaled inflows and reservoirs with some similarities to the Pacific Northwest. Reservoir refill differs depending on whether it endeavors to maximize economic gain from sale of hydroelectricity or minimize peak river flow consistent with flood risk management operations. However, operations driven by the two objectives appear not to be radically different.

References

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