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Water Supply and Energy: Relationships Between Snowpack, Streamflow, and Hydropower in the Snake River Watershed

Verena Eve Preucil

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Acknowledgments
I would like to express my sincere gratitude to my capstone advisory committee for your kindness, support, expertise, and time. I appreciate your guidance along every step of the way and your patience with my learning curve. To Nathan and Mitch, for keeping me grounded in what is relevant. To Dan, for all things water and climate. Special thanks to Mark Merrifield for your countless hours helping me in MATLAB and your unwavering support and enthusiasm. I would also like to thank Aly Bean and Jillian Hansen for encouraging me to explore this topic and connecting me to Mitch and Nathan. Thank you Corey and Hannah for being our fearless leaders in tackling the climate crisis. Thank you to my entire CSP cohort for being unwavering supporters during the long hours in Eckert and a sounding board for ideas. Thank you to my family, friends, and partner for being my cheerleaders throughout this experience.

Table of Contents

Abstract

Climate change is impacting water supply in the arid and semi-arid West; landscapes that already consistently weeks or months without a drop of precipitation. Hydropower has served as the backbone of energy supply in the West, but as it relies on water supply, it is vulnerable to climate change. This study explores the relationships between snowpack, streamflow, and hydropower at the Lower Granite Dam in the Snake River watershed. We found consistent declines in streamflow and snow-water-equivalent as well as significant correlations between snowpack, streamflow, and power production. We created a model that uses Variable Infiltration Capacity (VIC) variables to estimate streamflow and power production and demonstrates the important and direct reliance of energy production upon snowfall in the West.

1. Introduction/Motivation

Water supply in the arid West is integral to making decisions about land use, energy production, and conservation. As we move toward decarbonizing the energy grid in the face of climate change, understanding the ways in which changing water supply is influencing current and future energy production will become increasingly important. Climate change is anticipated to impact water supply through changes in precipitation as well as temperature, both as gradual changes as well as increases in extreme weather events. In the last decade, the West has experienced extreme drought and the resulting forest fires and fallowed land. The region has also seen the opposite end of the spectrum: record-breaking snow and rain in winter 2022-2023 in the western U.S. has caused catastrophic landslides and flooding. The timing, form, and amount of precipitation all play important roles in determining the availability of water in the West. Warming temperatures can also impact water supply even without changes in precipitation through increases in evaporation and evapotranspiration, and preventing snowpack accumulation. Federal hydropower produced in the Columbia River Watershed currently provides over 50% of the electricity generation for the watershed region from 29 major hydroelectric plants on the Columbia River and its tributaries as well as two in the Rogue River Basin (Interior et al., 2017). A large body of studies (Mote et al., 2018, Bales et al., 2006, Luce et al., 2014, Rangwala and Miller, 2012) have found that as temperature has warmed in the west, snow accumulation and snow melt have declined. Roughly 80% of streamflow in the West currently originates as snowfall rather than rain (Pagano & Garen, 2010). Snow provides the advantage of storing water through the winter to be released by snowmelt in the spring and summer. As climate change alters snowfall it begs the question: How reliable will the energy produced by hydropower be in the future climate?

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The future of hydropower will be a balance between changing precipitation, higher temperatures, and a shifting energy demand (Kao et al., 2022). The effect of climate change on hydropower is highly variable and dependent upon local geography and small-scale impacts. Researchers predict that some areas will see an increase in production ability, some will see a decrease, and others will not see a significant change at all (Wasti et al., 2022). In most cases it will not be the amount of hydropower that changes significantly, but the timing of generation capacity throughout the year. The four Lower Snake River Dams in Washington state are federally-owned run-of-river hydropower projects and are therefore completely dependent on the amount of water flowing through the river for power production. Streamflow is a result of precipitation (snow or rain) and evapotranspiration, both of which are controlled by temperature and thus affected by a changing climate. As extreme summer temperatures increase, the demand for air-conditioning may significantly shift the timing of peak electricity demand. Additionally, as more and more of the economy becomes electrified and the country shifts toward decarbonized and electrified systems, the reliability of current carbon-free energy production will become increasingly paramount to planning. Reservoir operations were established at the time of construction, much of which occurred in the mid-1900s, with few updates since. Wind and solar projects are expected to expand to help meet the rising demand for renewable energy; most of these projects will occur in rural America, such as the arid West. Understanding how water scarcity may play into the production capabilities of current infrastructure will be essential to determine how much more renewable infrastructure will be needed. Additionally, as water scarcity strains resources for both hydropower and agriculture, difficult land use decisions will have to be made.

This case study focuses specifically on the impact of climate change on the Lower Snake River Dams. The four Lower Snake River dams are the largest hydroelectric dams on the Snake River and together they provide over 1000 megawatts of energy annually to the Northwest. Since Idaho covers most of the Snake River watershed and provides the water for these dams, special attention is paid to Idaho's changing climate. 60% of annual precipitation in Idaho falls in winter months (Kunkel & Pierce, 2010). As climate change continues to increase temperatures, we are seeing a shift in precipitation: snow accumulation is decreasing, snowmelt is occurring earlier, more rain is falling, and summer temperatures are increasing in intensity and duration. The 2023 Energy Landscpe report for Idaho foresees an increasing deficit in energy production, both as a result of underproducing renewable energy and increasing demands on energy as the population expands. As such, understanding the role that changing snowpack plays in current power production is essential for future planning (Kao et al., 2022, Kliskey et al., 2019, Xu et al., 2014).

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This case study investigates how climate factors are influencing streamflow in the Snake River and the resulting consequences to hydropower on the Lower Granite Dam as it attempts to answer the following research questions: How is the water supply in the Snake River Watershed changing? Are there significant trends in snow storage and streamflow? Are modeled snow-water equivalent values able to accurately estimate power production? And finally, with climate change altering the water supply, can we rely on the lower Snake River dams to continue providing a significant portion of energy to the PNW? The Lower Granite Dam is the furthest upstream of the four dams on the Lower Snake, and because they are run-of-river dams, the outflow from the Lower Granite Dam flows into the subsequent three dams, indicating that it is a good representation of how production at all four dams is changing.

2. Background and Context

2.1 Changes to the region's climate

Precipitation

The observed and projected changes in precipitation in Idaho due to climate change have been variable. Projected amounts of precipitation have high uncertainty as it seems highly dependent on the localized environment. However, there is much more certainty surrounding the form and timing of precipitation. More precipitation is falling as rain rather than snow, altering the hydrograph. Rainfall increases the concentration of flows as it enters the river system immediately. Snowpack stores the water contained in snow and melts gradually throughout the spring and summer, providing a slow and lagged release into the river systems. This can cause an imbalance between power generation and power consumption as summer streamflow decreases but summer energy demand increases (Kao et al., 2022). Overall, the snowpack is expected to decrease, and in some locations, quite dramatically (Mote et al., 2018). Additionally, the peak spring snowmelt has been observed to be occurring on average 2 weeks earlier than before 1950 (Abatzoglou et al., 2021). Although two weeks may not seem significant to some, the melt timing and size greatly impact agricultural decisions, reservoir management, and hydropower generation.

Kunkel et al. (2010) showed that in the past 100 years, there have been three eras of snowmelt. In the 1920s &1930s, there were intervals of years with early snowmelt punctuating an otherwise consistent snowmelt. The 1940s to 1970s showed later and more consistent snowmelt size and timing. The most recent period, from the 1980s to ~2010 was characterized by variable and early snowmelt; some years the snowmelt volume was large, other years small, but consistently occurred earlier (Kunkel & Pierce, 2010). These eras likely have some relationship with Pacific Decadal Oscillation (PDO) which was in a negative phase from the 40s to the 70s, a positive phase from the late 70s through to 1998, and a negative phase from 1999 to 2012 (NASA, 2020). Pacific Decadal Oscillation (PDO) refers to sea surface temperatures in the Northern Pacific Ocean and is associated with long-term El Nino (positive) and La Nina phases (negative). La Nina is correlated with a higher frequency of extreme precipitation and streamflow events in the Northwest (Cayan et al., 1999). While informative, these phases do not explain the full extent of snowpack decline (Li et al., 2020).

Temperature

Temperature changes from climate change are much more certain than precipitation changes. Since 1895, Idaho has seen an average increase in temperature by 1.8°F. The elevation of the freezing level has increased by over 500 feet since 1950 and the length of the freeze-free season has increased by 2 weeks (Abatzoglou et al., 2021). High latitudes are warming at faster rates than low latitudes, and the fastest warming has been observed in winter and spring between 30° and 90° (Xia et al., 2014). Many studies suggest that high-altitude areas are warming at a faster rate than lower-elevation zones of the same latitude, but these trends vary geographically and are sometimes contradicted with other studies suggesting that lower elevations are warming faster than their high-elevation counterparts (Rangwala & Miller, 2012). There are several mechanisms that drive enhanced warming trends. In addition to increases in atmospheric carbon dioxide increasing absorption of infrared radiation, snowy regions experience positive feedback as high temperatures increase snowmelt, and the loss of snow and ice decreases the albedo of the area, in turn increasing solar absorption and further warming (Rangwala & Miller, 2012).

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The Intergovernmental Panel on Climate Change (IPCC) has outlined several different political and economic scenarios under which to simulate climate change from the resulting carbon emissions. These are called the Representative Concentration Pathways (RCP) and range from RCP 2.6 to RCP 8.5. The numerical value represents the radiative forcing in the atmosphere caused by greenhouse gases by the year 2100. RCP 2.6 is the highest level of effort to curb emissions, RCP 4.6 is a medium-to-high effort to curb emissions, RCP 6.0 is a medium-to-low effort, and RCP 8.5 is low to no effort. Under RCP 8.5, Idaho's mean annual temperature is projected to increase by 11°F, and under RCP 4.5 it will warm by 6°F by 2100 (Abatzoglou et al., 2021). This increase includes a slightly more dramatic increase in winter temperatures than summer temperatures Winter warming can cause drought in mountainous areas simply by preventing snowpack accumulation or shortening the melting period (and therefore shortening the water supply) (Mote et al., 2018). The number of severe heat days in the summer months is projected to increase significantly. Rising temperatures increase evaporation from surface water as well as evapotranspiration rates in plants and soils, increasing their demand for water. Those two feedbacks reduce the overall water supply and result in temperature changes being the main driving force in streamflow changes in projected climate scenarios.

Oceanic Nino Index (ONI) refers to sea surface temperatures over the Nino 3.4 region near the equator in the Pacific Ocean and is associated with the El Nino Southern Oscillation (ENSO) phenomenon. An elevated temperature in the Pacific Ocean is associated with the El Nino phase, and decreased temperatures are associated with the La Nina phase. Both short and long term El Nino is associated with higher temperatures across Idaho (Sohrabi et al., 2013), and some studies suggest that climate change may increase the frequency of extreme El Nino events (Cai et al., 2014).

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2.2 Snake River watershed geography

The Snake River begins in Wyoming, flows west through southern Idaho, and then turns north to create the border of Oregon and Idaho, before turning west again and entering the Columbia River in Washington. It is the largest tributary to the Columbia River, which in turn is the largest outlet to the Pacific Ocean in North America. The Snake River watershed consists of high mountains, desert plains, forests, and agricultural regions. The highest elevation in the watershed is over 12,000 feet, while the river's confluence with the Columbia River is at just 340 feet. The many dams on the Snake River and its tributaries have historically provided more than two-thirds of Idaho's energy generation although drought and dwindling streamflow have reduced that number to just about 50% (Idaho Office of Energy and Minerals, 2023). Additionally, the Snake River and its aquifers beneath the Snake River Plain in southern Idaho provide irrigation water to 3 million acres of farmland (*Snake River plain aquifer,* 2023*)*. The Snake River watershed collects snow that falls from the continental divide along the border of Montana to the border of Oregon and the Snake Plain in the south (Kunkel & Pierce, 2010). As such, much of the precipitation that falls in Idaho winds up in the Snake River its aquifers, indicating that snowfall trends will play a significant role in the future of hydropower production as well as irrigation and agricultural decisions.

Figure 1: The Snake River Watershed

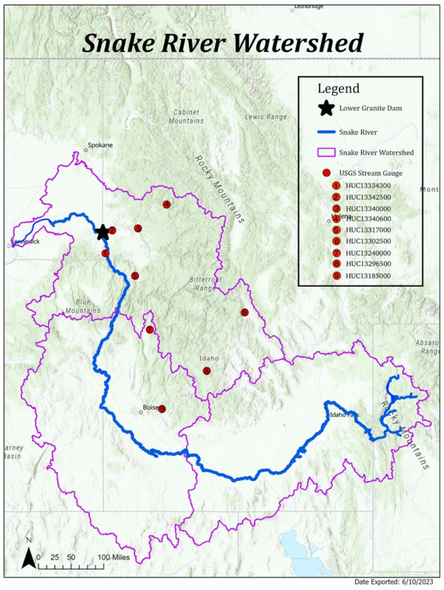

Figure 1: The Snake River watershed

2.3 Power Production

The Bonneville Power Administration (BPA) is the power marketing administration for federally-owned hydropower in the Pacific Northwest (PNW). BPA's energy infrastructure is 90% carbon-free, 85% of which is hydropower. BPA provides these energy services to 60% of the population within their service area (*Hydropower Impact,* Interior et al., 2017). There are 22 hydropower dams on the mainstem of the Snake River, and many more on its tributaries. Of those 22, 15 are in Idaho, 3 are on the Idaho/Oregon border, and the 4 largest (the lower Snake River dams) are in Washington (*Snake River,* 2023*)*.

79% of Idaho's electricity consumption comes from carbon-free sources, the majority of which is hydropower. There are 140 hydropower dams in Idaho, supplying around 50% of the state's electricity needs. The remainder of in-state renewable electricity is mostly wind and solar, with a small amount of geothermal (Idaho Office of Energy and Minerals, 2023).

Hydropower is the energy source that allowed the development of the West. In the 1900s, most energy was either coal or hydro, and the West largely chose hydro. Moving forward with decarbonization, many scenarios utilize hydropower as a grid balancer.

2.4 Impact of Dams on Ecology

It is well-documented that large hydropower dams make it difficult for fish to migrate from and to their spawning grounds. The Snake River and its tributaries are home to five species of salmon and steelhead fish, which make a journey of hundreds of miles to and from the Pacific Ocean. Fish abundance has declined by over 90% since the mid-19th century. While most dams have mitigation measures meant to aid fish recovery including fish ladders and increased streamflow during fish migration season, a recent NOAA report found that hydropower dams have the largest negative impact on their ability to return to their natural spawning grounds from the ocean (United States, 2022, LSRD Benefit Replacement Report, 2022).

2.5 Land Acknowledgement

The Snake River and its tributaries flow through the ancestral lands of the Burns Paiute, Umatilla, Yakima, Nez Perce, Colville, Wanapum, Coeur d'Alene, Kalispel, Kootenai, Northwestern Band of the Shoshoni Nation, Shoshone-Bannock, Shoshone-Paiute, Confederated Tribes of the Warm Springs Reservation of Oregon, and the Spokane Tribes (*Native American Concerns*, 2023). Their cultural and historical sites are located throughout the basin, many of which they no longer have access to. Fish are also considered integral to their way of life and livelihoods. Several tribes signed treaties in the mid-1800s which ceded millions of acres of the basin to the federal government. However, they reserved the right to fish at their historical fishing grounds. Today, many of those places are either inaccessible or the number of salmon returning is too low to sustain the tribe any longer. Without access to this important natural and cultural resource, it is more and more difficult for tribes to uphold their culture, language, and religious ceremonies (LSRD Benefit Replacement Report, 2022).

3. Methods

The Variable Infiltration Capacity (VIC) model is a macroscale gridded hydrology model that estimates energy and water fluxes on land and between the land and atmosphere. It runs each gridded cell independently and then maps estimated surface and baseflows for the entire grid. CMIP 5 is the fifth phase of the Coupled Model Intercomparison Project and is a combination of 40 different Global Circulation Models (GCM) from 20 different working groups. We used variables from a VIC model forced from downscaled CMIP5 projections. VIC historical daily-averaged time series of regional surface air temperature, snow-water equivalent (SWE), and total runoff were obtained for the region bounded by (40°-50° latitude and 109°-120° longitude), which includes the Snake River watershed. The model time series span 1915 to 2013. SWE measures the volume of water stored in snow and is typically used to estimate water supply from snow. Total runoff in the model represents streamflow that persists between precipitation events, plus runoff, defined as the unconfined flow of surface water over a surface and is the resulting water that was not able to infiltrate the soil and includes excess water from weather events.

Stream gauge data operated by the United States Geological Survey (USGS) were obtained for nine locations along the Snake River and its tributaries (Figure 1). Daily-average time series of river discharge in cubic feet per second at all sites cover the time period 1967 to 2023, although individual locations' start date varies, the earliest of which is in 1925. In this study, we focus primarily on the stream gauge HUC13334300. HUC13334300 is located on the Snake River at Anatone, WA and is the stream gauge located closest to the Lower Granite Dam. Out of the several stream gauge sites analyzed, this site was chosen for direct correlation with power production and for the VIC model because it is the closest gauge to the Lower Granite Dam and is on the Snake River. The other stream gauges analyzed in this study are located throughout the watershed and represent significant tributaries that eventually end up in the Snake River. Since this stream gauge is located downstream of the Hells Canyon Dam, as well as downstream of the several dams located on tributaries to the Snake, it is not immune to human influences. That said, reservoir operations are still largely dependent on the conditions of the current water year and are therefore subject to climatic trends. For this reason, we expected to see climate signals despite the human manipulation upstream of the stream gauge (Figure 1).

Water outflow and power production records for the Lower Granite Dam were obtained from the US Army Corps of Engineers. The power production data represents monthly total production in megawatt hours (MWh) for the years 2001-2021.

Two different climate normals were calculated, a historic normal from 1960-1990 and a recent normal, from 1990-2020. These periods were chosen to encompass the greatest amount of data for all VIC and streamflow inputs, considering the variation in record length across stream gauges and the VIC model. VIC data ranges from 1915-2013, so it encapsulates the full historic normal but the recent average is only 23 years, from 1990-2013. Seven out of the nine stream gauges have records that start before 1960 (five begin in 1948, one in 1924, and one in 1958), so those seven have both complete climate normal periods, 1960-1990 and 1990-2020. Two begin after 1960, one begins in 1963 and one begins in 1968. Those two gauges have incomplete historical normal (27 and 22 years in length, respectively) but complete recent normal.

Seasonal means of the VIC variables were formed over historical and recent climate normal periods, defined above. Composite maps of anomalies from the seasonal means were computed for those time periods as well as for years of maximum and minimum dam flow capacity to provide power production and irrigation services. Winter was defined as January through March, spring as April through June, Summer as July through September, and Fall as October through December. Maximum and minimum dam capacity years are 1974 and 1937, respectively. Anomalies for those years were calculated from a 30 year climate normal encompassing the year in question. For 1974, the climate normal was calculated for 1950-1980, in order capture the majority of the negative phase pacific decadal oscillation (PDO) which lasted from the 1940s to 1970s (NASA, 2020). For 1937, the climate normal was calculated for 1920-1950, to avoid the influence of the negative phase PDO as much as possible.

Using stream gauge data, we compared historical and recent climatological normals as well as found the peak production and cumulative streamflow trends for each site.

We formed monthly averages of all datasets in MATLAB and investigated the degree to which river discharge at HUC13334300 station could be hindcast from VIC air temperature, SWE, and runoff. We made these estimates for each month of the year, i.e., we use January SWE to estimate January discharge. For each month of the year, we computed correlations between discharge and each of the three variables at every model grid cell in the domain spanning the Snake River watershed. We constructed an estimate of discharge for each month based on runoff and SWE, by computing a correlation-based weighted average using grid cells that had at least a correlation of 0.6 with the discharge time series. A least-squares fit was used to determine a slope and intercept to convert the weighted average to discharge. For some summer months, computed correlations did not meet the 0.6 thresholds, in which case no hindcast prediction is made for that month. Air temperature generally was not well correlated with discharge, making this variable a poor predictor of discharge on its own. We used weighted averages of SWE and air temperature and the SWE +Tair-discharge correlations, to compute an estimate of discharge based on a linear combination of SWE and air temperature. A multiple regression was used to determine the regression coefficients and offset term.

The power production at the Lower Granite Dam (LGD) was regressed on the streamflow discharge at HUC13334300 for each month of the year. The slopes of the regression (one for each month) were used to estimate power from the streamflow estimates created using the VIC model. Dam power production also was analyzed to identify peak production and the yearly distribution of production.

4. Results

4.1 Seasonal and interannual variability

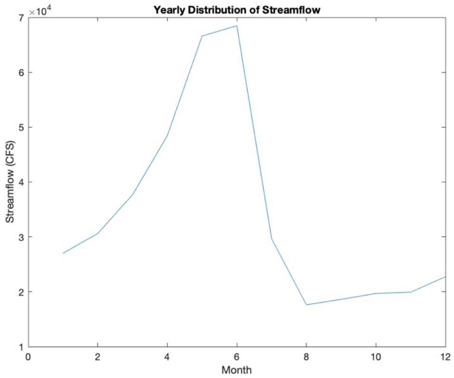

Figure 1: Yearly distribution of streamflow at HUC13334300 formed from monthly averages across all years of record (1958-2023)

Figure 1 shows the seasonal distribution of streamflow at site HUC13334300 across the calendar year. There is a steep ramping up in the winter and spring months before reaching the peak streamflow in June. It then sharply declines over the following two months to reach the minimum streamflow in August. After August, the streamflow increases slightly and slowly for the rest of the year.

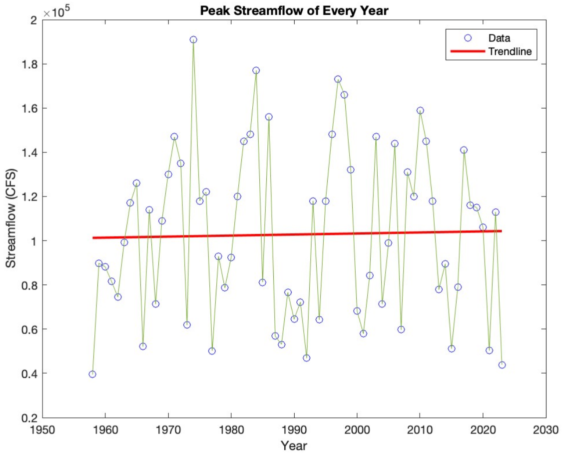

Figure 2: Maximum streamflow every year at HUC13334300 for the duration of the record.

Although there is a large amount of variability in peak streamflow throughout the year, HUC13334300 shows no visible trend (Figure 2). Out of the nine stream gauges analyzed, four showed declining trends in peak streamflow and the remaining five showed no trend (Appendix 8.1).

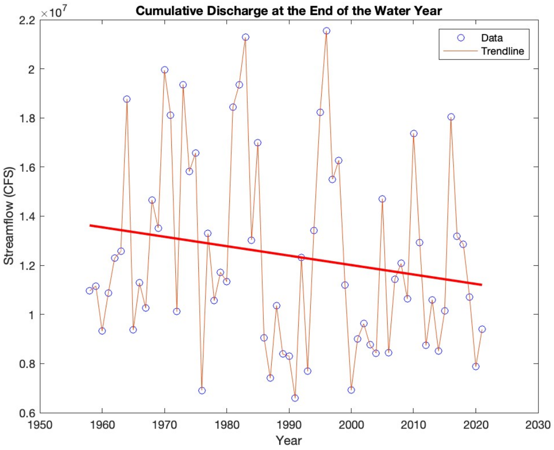

Figure 3: Cumulative discharge at the end of water year (September 30) with a trendline calculated from polynomial coefficients calculated for each data point

Six out of the nine stream gauges analyzed showed decreasing trends of cumulative discharge at the end of the water year and the remaining four showed no trend (Figure 3, Appendix 8.1).

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4.2 Recent patterns verses climate normal

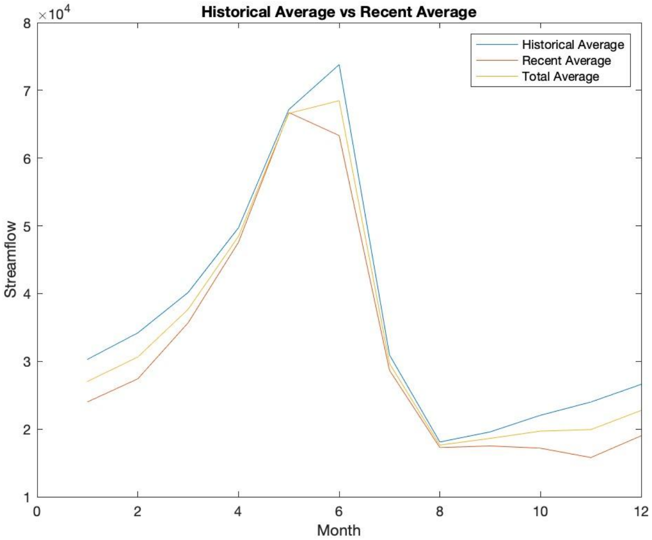

Figure 4: Yearly distribution of streamflow at HUC13334300 comparing historical normal (1960-1990), recent normal (1990-2020), and the total record length (1958-2023).

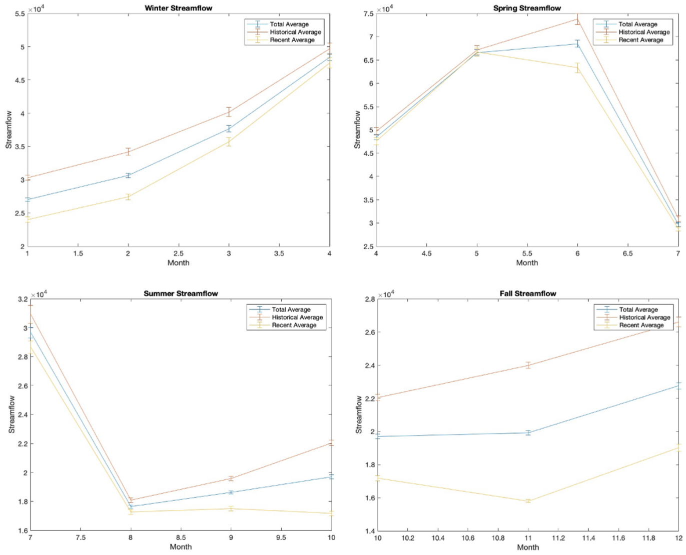

Figure 5: Seasonal differences between historical, recent, and total averages. Error bars calculated with standard deviation.

Figures 4 and 5 show the seasonal distribution of streamflow at HUC13334300. The overall trend is low streamflow that builds rapidly in March and April, peaks in May or June, and then quickly declines to low levels by August. The historical climate normal has consistently higher streamflow than the most recent climate normal, with the greatest discrepancies in October and November. Additionally, the peak streamflow in the historical normal occurs in June, while the recent normal peaks in May. In both figures you can see that the total average, which averages the entire 66-year dataset, is lower than the climate average but in places, higher than the recent average. The 1970's, which are included in the climate average, were notoriously snowy and could be influencing the high levels of streamflow in the historical average. Conversely, the 1930s were the Dust Bowl era, and while the Dust Bowl is primarily known for drying out the Midwest, it was equally extremely dry in the West and could be influencing the low levels seen in the total average. However, more significant than the levels is the shape of the curves in the spring months. Both the climate and the total averages see peak streamflow in June, while the recent average sees peak streamflow in May. Streamflow then drops to levels lower than those seen in both total and climate averages for the summer and fall. The trends shown in figures 4 and 5 are consistent with the other stream gauges analyzed, although there is some variability in particular timing and trends. Eight out of the nine stream gauges showed overall decreases in streamflow when comparing the historical climate normal to the recent climate normal. Three showed declines in winter streamflow, three showed increases in winter streamflow, and three showed decreases in January but increases in March. Eight stream gauges showed declines in spring and summer streamflow and all nine showed declines in fall streamflow.

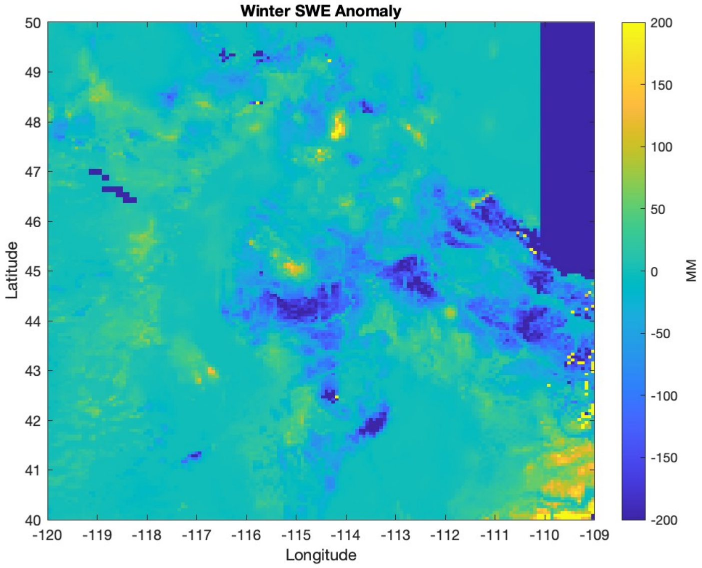

Figure 6: Winter SWE anomaly of recent average (1990-2015) subtracted from historical average (1960-1990)

Figure 6 shows of the recent climate average (1990-2013) anomaly from the historical climate average (1960-1990). The anomaly is calculated by subtracting the recent climate average from the historical climate average. Much of the snowpack remains unchanged between time periods although a fair amount of area sees a decrease of up to 200 inches in SWE. A smaller amount of area sees some increases in SWE from between 50-200 inches.

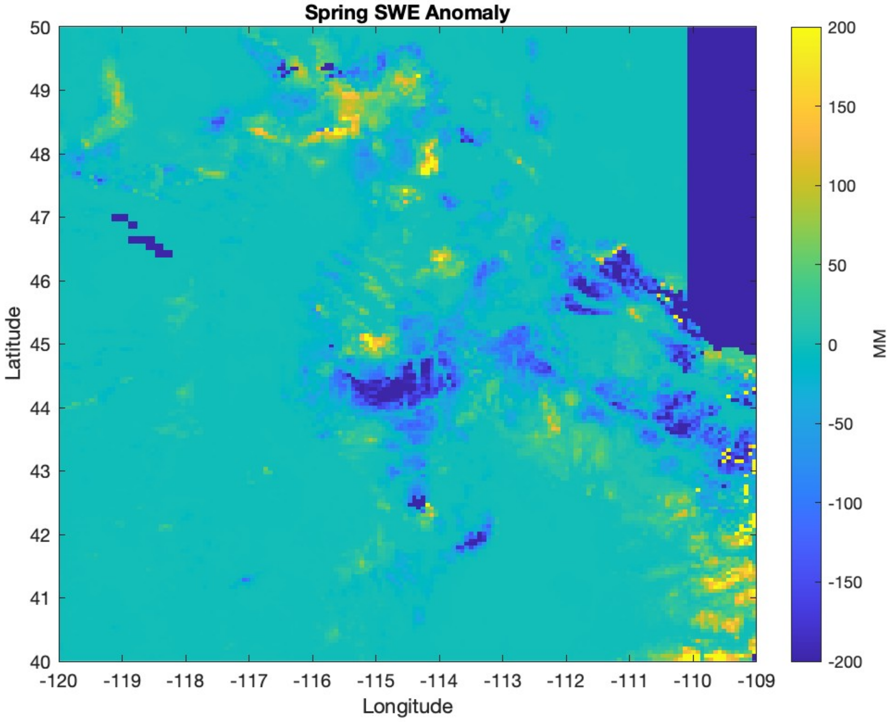

Figure 7: Spring SWE anomaly of recent average (1990-2015) subtracted from historical average (1960-1990)

Figure 7 shows that there is a similar pattern in spring as there is in winter: a concentrated decrease in SWE in the middle of the watershed as well as sparse increases throughout.

Summer and fall showed minimal changes from the climate normal. Overall, spring and summer showed generalized increases in average temperature when comparing the recent time period to the climate normal while winter and spring showed a blotchy pattern of both increased and decreased average temperatures.

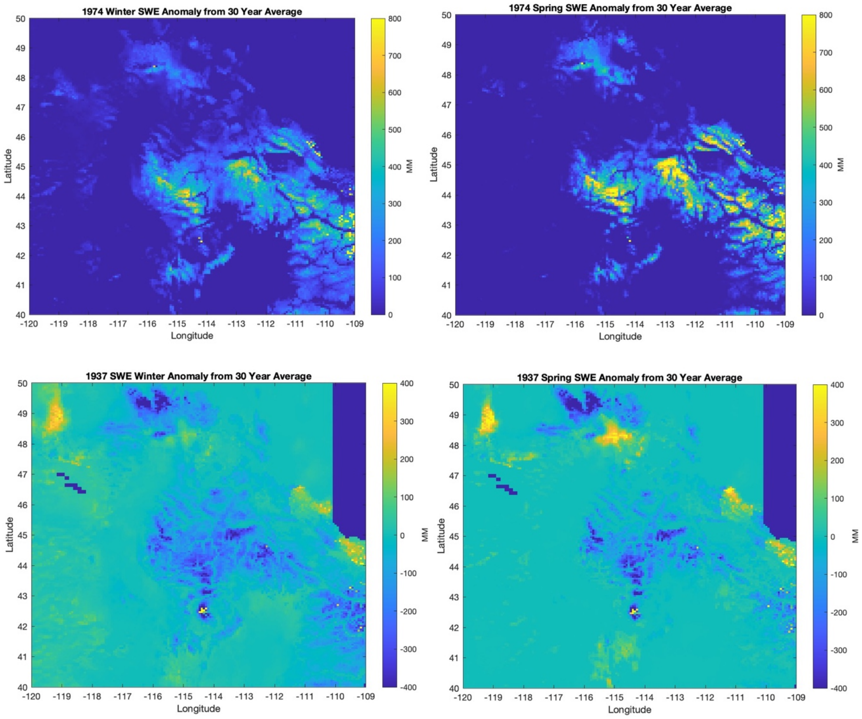

Figure 8: Winter and spring SWE anomalies for the years 1974 and 1937. Anomalies were calculated from the amount SWE deviated from a 30 year average surrounding that year.

The Lower Granite Dam operating procedures are based on predictions made from an 80-year average flow distribution. 1937 is used as a benchmark for minimum operational flows and 1974 is used as a benchmark for maximum operational flows. In 1974, both winter and spring SWE was between 300-800 mm (11-31 in) higher than the average, although the anomaly is greater in the spring. In 1937, winter and spring anomalies over the mountains in central Idaho were between 100-400 mm (3.9-15.8 in) below average, and up to 400 mm (15.8 in) higher in points. The winter anomaly was greater than the spring anomaly in 1937, and the deficit covered more ground than the positive anomaly.

4.3 VIC model correlations and discharge estimates

Commented [MM11]: As Dan suggests, don't use "prediction". I suggest "estimate".

Using VIC runoff, SWE, and temperature variables we correlated each variable with streamflow at HUC13334300 for each month. Using only those correlations that were 0.6 or higher, we estimated streamflow for the duration of the VIC model time series, 1915-2013.

Runoff was correlated in the highest number of months, followed by SWE. Annual air temperature by itself was not significantly correlated with annual discharge at any point or location within the study area bounds, but combining air temperature with SWE gave the most correlated estimates. We also correlated VIC air temperature to VIC runoff and VIC SWE and found that air temperature and runoff are highly correlated (between .7-.9) in the mountainous region of the watershed during April, fairly correlated in March (.5-.9), but not significantly correlated in any other month (Appendix).

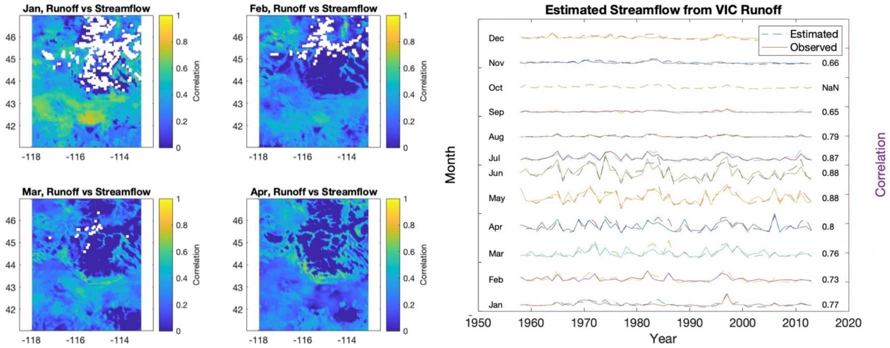

Figure 9: Estimated streamflow at HUC13334300 from VIC runoff. Correlations were calculated for each month and used to estimate streamflow if they were 0.6 or higher. White areas indicate values of zero.

Runoff from the VIC model and streamflow on the Snake River have correlations over 0.6 in eleven out of twelve months of the year (Figure 9). The most highly correlated months are in spring and early summer: April, May, June, and July. The correlation varies spatially as well. In winter months, the correlation is found in the western and southern regions of the watershed, typically associated with lower elevations. In the spring, the correlation shifts into the northeastern part of the watershed, which generally encapsulates the mountains in central Idaho.

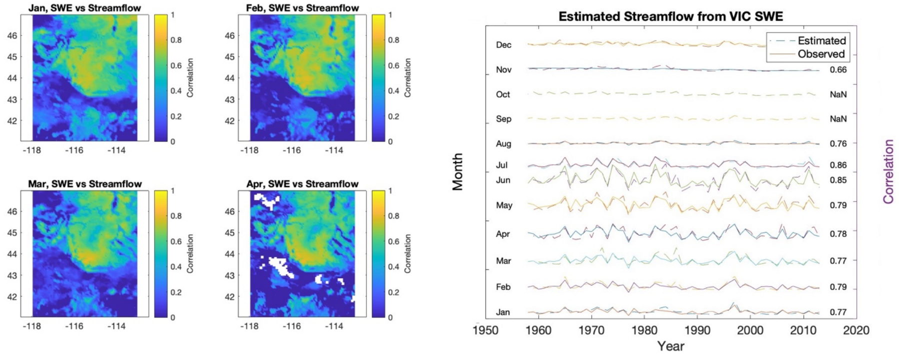

Figure 10: Estimated streamflow at HUC13334300 from VIC SWE. Correlations were calculated for each month and used to estimate streamflow if they were 0.6 or higher.

SWE from the VIC model and streamflow on the Snake River have correlations of 0.6 or higher in ten out of twelve months (Figure 10). Both the temporal and spatial correlation between SWE and streamflow have similar patterns to the correlation between streamflow and runoff. The spatial correlation of SWE and streamflow is consistently located in the northeastern part of the watershed, likely because most of the snowfall occurs in that area. The highest correlated months are June and July, although the entire winter and spring are quite highly correlated. The white areas are locations with values of zero because there is simply no snow in those places during certain times of the year.

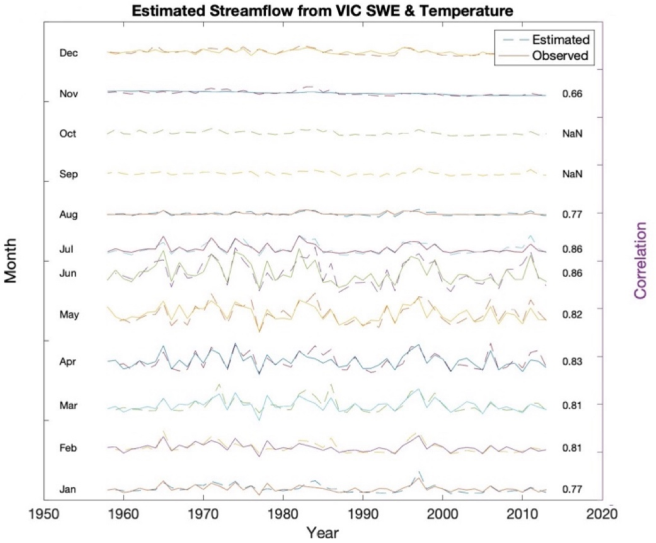

Figure 11: Estimated streamflow from VIC SWE and surface air temperature variables based on correlations formed for each month.

Figure 11 shows an estimation model with both VIC SWE and air temperature models as the predicting variables and streamflow as the output. Again, the two months where there is no correlation are September and October.

Month	**Correlation Coefficient**
January	0.600
February	0.695
March	0.432
April	0.803
May	0.457

June	0.782
July	0.830
August	0.225
September	NaN
October	NaN
November	-0.068
December	0.886

Table 1: Monthly correlation values for estimated temperature and observed streamflow between the years 1958-2013

Table 11 shows the correlation coefficients for the modeled temperature index and observed streamflow at HUC 13334300. Spring is highly correlated between April and July, indicating that springtime temperatures have a large impact on streamflow.

4.4 Model generated specifications: using snow water equivalent to estimate streamflow

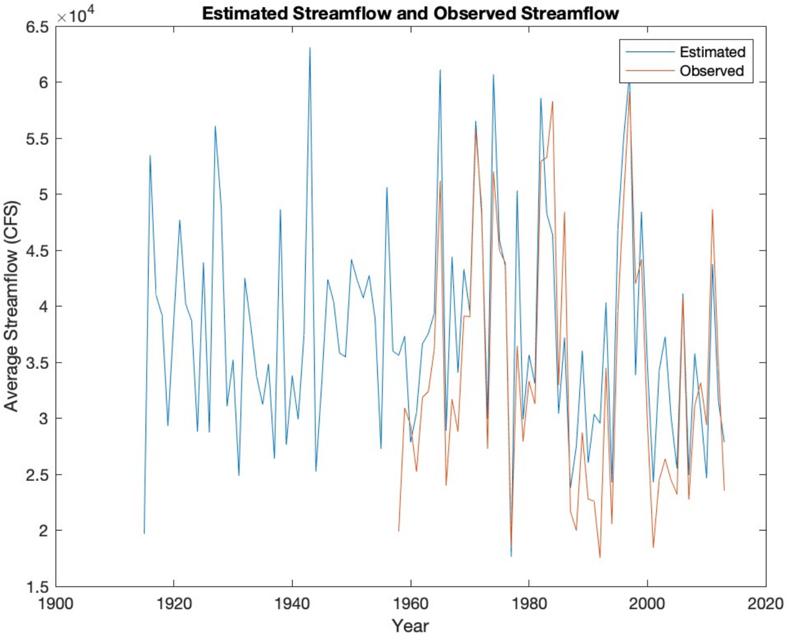

Figure 12: Streamflow estimated from VIC SWE + temperature aligned with observed streamflow from HUC13334300. Streamflow was averaged for every month of every year and plotted consecutively.

From the correlational relationships shown in figure 11, we used the full record of SWE to estimate discharge going back to 1915 (figure 12).

Figure 10 shows streamflow predicted by the model using monthly averaged SWE and surface air temperature as the predictor variables. The predicted streamflow is in blue while the observed streamflow is in red. For the time period that the observed record overlaps with the predicted, the predicted pattern matches the observed pattern and has a correlation of 0.6 or higher in ten out of twelve months and a correlation of 0.8 or higher in six months with a RMS value of 0.79 (Table 2). There are some instances where the predicted streamflow overestimated what was observed and some instances when the observed was higher than the predicted. The pattern of which years would be peaks and which years would be valleys is noticeably aligned between the two stream flows, showing that for the past 100 years, SWE has been a dominating force to predict streamflow.

Commented [MM12]: Is this for a specific month? All months? Yearly average?

Month	**Correlation**
January	0.77
February	0.81
March	0.81
April	0.83
May	0.82
June	0.86
July	0.86
August	0.77
September	NaN
October	NaN
November	0.66
December	0.77

Table 2: Monthly correlation values for estimated and observed streamflow between the years 1958-2013

4.5 Model generated specifications: using snow water equivalent to estimate power production

Power production, outflow from the dam, streamflow, and snow-water equivalent (both in the hydrology model as well as observed data sets) all show the same pattern: increasing levels throughout winter, a peak in late spring/early summer, followed by a sharp decline through summer and reaching a minimum in August.

Commented [MM13]: I agree with Dan. Spend some time describing first the discharge since this is what you're mainly interested in predicting. Show the seasonal cycle, time series of monthly averages, time of max, time of min, etc.

Then show seasonal averages and monthly time series of SWE, runoff, and Tair. For simplicity, average these variable over the spatial domain so that you have one time series and one seasonal cycle for each.

There are high correlations between outflow and power, streamflow and power, and snow-water equivalent and streamflow in winter and spring months. The correlations dip to insignificance in summer and fall, likely because we did not account for a lag effect. Ie, snow levels in June continue to affect streamflow levels in July, even if it has all melted by the beginning of the month.

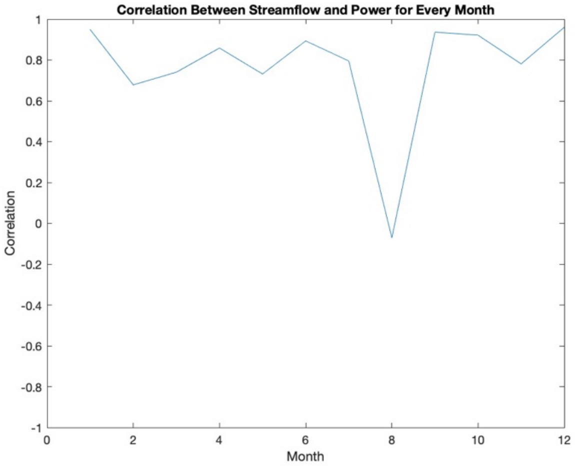

Figure 13: Correlation between streamflow at HUC13334300 and power production at the Lower Granite Dam

Streamflow at HUC13334300 is highly correlated with power production at Lower Granite Dam for every single month except for August. The low correlation in August is likely due to a shift in operational procedures as the dam prioritizes flows for fish passage over power production.

Commented [MM14]: Move figure 2 and this section after you develop the model for discharge. List the slopes vs each month of the year in a table. Show observed and estimated power in 12 time series plots for each month. List the correlation between the two variables.

Month	Correlation
January	0.95
February	0.68
March	0.74
April	0.86
May	0.73
June	0.89
July	0.80
August	-0.07
September	0.94
October	0.92
November	0.78
December	0.96

Table 3: Monthly correlation values between streamflow at HUC13334300 and power production at LGD between 2001-2021.

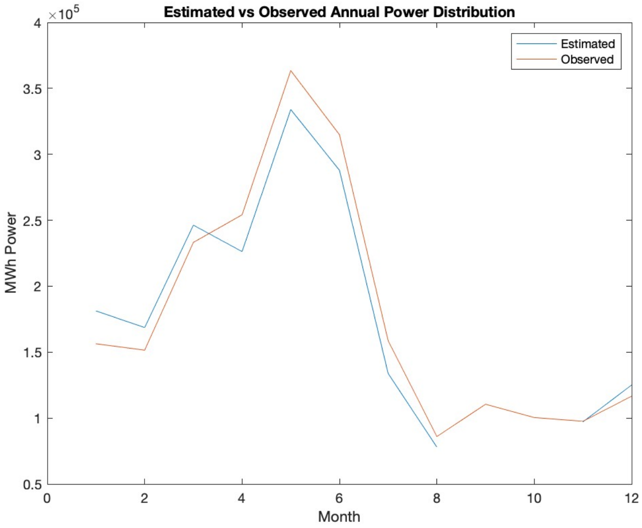

Figure 14: Annual distribution of power production for estimated and observed data series. Both data sets were clipped to overlapping years, 2001-2013.

The model tends to overestimate winter power production and underestimate spring and summer production. However, the difference is never greater than 30,000 MWh between the estimated and observed values (figure 14). The estimated and observed values have correlations of 0.6 or higher in five months and have an RMS value of 0.53.

Month	Correlation
January	0.60
February	0.69
March	0.43
April	0.80
May	0.46
June	0.78
July	0.83
August	0.22
September	NaN
October	NaN
November	-0.06
December	0.39

Table 4: Monthly correlation values between estimated power production and observed power production from a data series clipped to overlapping years: 2001-2013.

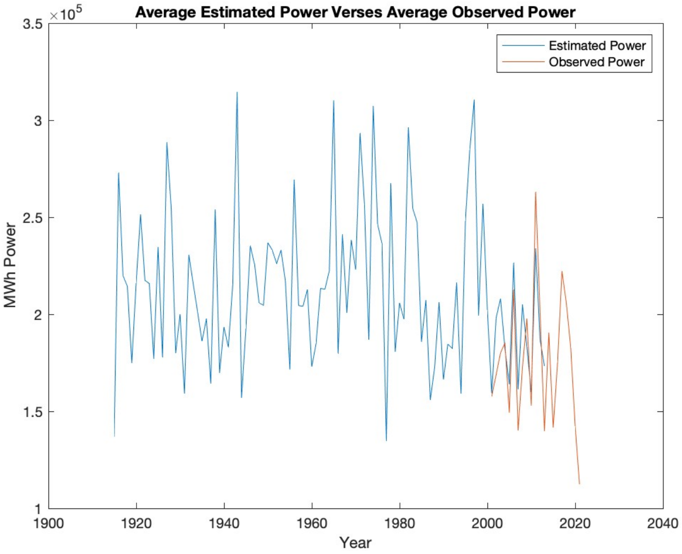

Figure 15: Estimated average monthly power for the timeseries of the VIC MODEL, 1915-2013 aligned with the 20 year time series of observed power production

Estimated power production aligns well with observed power. There are discrepancies in some years, notably there early 2000s saw a large overestimation of power production and 2011 underestimated power production.

5. Discussion

It is well known that most of the water supply in the West originates in the form of snow, and our model was able to demonstrate the significance of that at a fine scale. Using VIC SWE and air temperature averaged across the watershed, the model was able to estimate streamflow at one site on the Snake River with significant accuracy. Since the outflow of the Lower Granite Dam, streamflow on the Snake River, and power production from the dam are all highly correlated, we could use the relationship of snow and streamflow to estimate power production. The Lower Granite Dam (LGD) is the most upstream of the four Lower Snake River Dams, and all of the water that flows out of the LGD flows into the other three dams. We can therefore expect that the patterns and relationships found for the LGD can be extended to the other three dams further downstream. Once the Snake River joins the Columbia River, the watershed for the Columbia River expands to include vast swaths of the Pacific Norwest. Mote et al. (2018) clarified that while precipitation is the primary driver of water supply in the

Rockies, fluctuations in temperature have a greater influence on water supply in the Pacific Northwest (Mote et al., 2018). The analysis done here utilizes both SWE and air temperature to estimate streamflow and power, so it could hold true for dams on the Columbia River in that respect. However precipitation in the form of rain plays a larger role in streamflow as you near the coast and at lower elevations, so the model would likely need to be corrected to include rainfall as well.

Winter and spring warming directly affect snow accumulation and melt by both limiting winter snow accumulation and increasing the speed of spring melt. Warm winter's generally result in a lower snowpack and a warm spring season generally causes snow to melt earlier and faster, leaving a longer dry season in the summer and fall. The VIC model showed patchy changes to winter temperature between the historical and recent climate averages but overall the increases in temperature were higher and covered more area than the decreases in temperature. It found increases in spring temperature by about 1° between the historical and recent normal (Appendix 8.4). Spring temperatures are understood to dictate the speed of snowmelt, with higher spring temperatures melting more snow faster and subsequently shifting the hydrograph for peak streamflow to occur earlier in the year (Pederson et al., 2010, Stewart et al., 2005). This also leaves less water available to maintain summer flows. It is possible that spring warming is partially responsible for the increasing fraction of streamflow occurring in May and decreasing fraction occurring in June, although further research would be needed to come to more thorough conclusions.

The mountainous regions of the Snake River watershed see temperatures at or near freezing between 40-70 days of the year. Additionally, 30-60% of large winter storms in the region occur during that time (Bales et al., 2006). This makes the watershed particularly vulnerable to rising temperatures, as an increase of just a few degrees could see a shift in the largest storms falling as rain rather than snow. The future climate in the Snake River watershed is predicted to see higher temperatures, with notable increases in extreme heat days during summer months at low elevations. It will also see a shift in the form of precipitation from snow to rain. The trend of precipitation falling as rain instead of snow has already begun. Abatzoglou et al. (2021) found up to a 15% decline in the ratio of precipitation that fell as snow vs rain since 1950 (Abatzoglou et al., 2021.). During that same timeline, we have also seen an overall decrease in streamflow, demonstrating runoff sensitivity to snowfall and temperature. Six out of the nine stream gauges analyzed showed decreases in cumulative streamflow, indicating a net decrease in water supply in the last fifty years. Eight gauges showed declines in spring, summer, and fall streamflow, further indicating declines in water supply. Additionally, the decline in water supply during the summer and fall is likely to have significant consequences for agriculture as warmer temperatures increase evapotranspiration and the crops' need for additional water during those increasingly dry months. This is consistent with Tang and Lettenmaier, who found that runoff shows a high degree of sensitivity to small changes in temperature (Tang & Lettenmaier, 2012). This indicates that further shifts into rainfall may not be enough to maintain summer streamflow. Mote et al (2018) showed that increasing temperatures can cause drought (determined by soil moisture content according to the Palmer Drought Index) by preventing snowpack from accumulating and therefore limiting the summer water supply (Mote et al.,

Commented [15]: Might first comment on warming in winter and spring which directly affects snow accumulation and melt. How much of the Idaho landscape has historical mean T that lies near freezing ? (there's an important Dettinger paper that illustrates this for at least CA and maybe other parts of the US)

Then, turn to warmer warm season and incr electricity and incr ET problems.

Commented [CD16]: Might first comment on warming in winter and spring which directly affects snow accumulation and melt. How much of the Idaho landscape has historical mean T that lies near freezing ? (there's an important Dettinger paper that illustrates this for at least CA and maybe other parts of the US)

Then, turn to warmer warm season and incr electricity and incr ET problems.

Commented [17]: Important to be clear / quantitative about:

- Change in precip
- Change in snow
- Change in runoff or streamflow
- Change in Hydropower

What does VIC data indicate
Do warming temps actually reduce streamflow (given no change in precip) ? this is called "runoff sensitivity", which hydrologists like Lettenmaier and colleagues have studied.

Commented [CD18]: Important to be clear / quantitative about:

- Change in precip
- Change in snow
- Change in runoff or streamflow
- Change in Hydropower

What does VIC data indicate
Do warming temps actually reduce streamflow (given no change in precip) ? this is called "runoff sensitivity", which hydrologists like Lettenmaier and colleagues have studied.

Commented [19]: Really?
Maybe you mean summer dryness??

Commented [CD20]: Really?
Maybe you mean summer dryness??

2018). This study reinforced those findings by showing the decrease in streamflow resulting from a decreasing snowpack.

The seasonal distribution of power production at the Lower Granite Dam aligns with the seasonal distribution of both streamflow and SWE. As the LGD is a run-of-the-river hydropower plant, its power production capacity is entirely dependent on water supply, which in the Rockies, is driven primarily by snowfall. 1937 streamflow represents minimum flow levels for power production operation. Our model estimates that streamflow has reached or gone below that level twelve times between 1937 and 2013, however observational data shows more extreme low flows during several of those years, including 2001. In 2001, the Lower Granite Dam produced a total of 1,890,964 MWh throughout the year. Conversely, 2011 saw SWE levels similar to those in 1974, and the power production in that year totaled over 3,156,258 MWh. The Lower Granite Dam produced the same or less power as 2001 in seven other years between 2002 and 2021, the lowest of which occurred in 2021 (Appendix 8.2). There were no other years between 2001 and 2021 in which the dam produced three million megawatt hours apart from 2011. The 2023 Idaho Energy Landscape attributes declines of 10% of power production in recent years due to drought (Idaho Office of Energy and Minerals, 2023). However, with the increasing frequency of low flow years, further research should be conducted to determine if these declines in power production represent a “new normal” due to climate change.

Right now, peak demand for energy within the region supplied by BPA occurs in the winter months when people are heating their homes. With increasing average temperatures as well as increased frequency of extreme heat days (days over 100°F), it is likely that the region sees a significant increase in summertime energy demand as more buildings require air conditioning. It is also possible that energy demand in the winter may fall slightly as temperatures rise, reducing the need to heat homes. However, population increases will increase demand for both heating and air conditioning. Hamlet et al found that overall, energy demands will increase as the wintertime demands from population growth are greater than the reductions as a result of winter warming. Additionally, population growth only compounds summertime energy demands (Hamlet et al., 2010).

This case study examined streamflow and snow water equivalent trends within the Snake River watershed from both observed and modeled data. It was able to use those variables to estimate power production at the Lower Granite Dam. There are many influences on climate that this study was too limited to explore. One such influence is the influence of ENSO and PDO, which are known to have effects on precipitation and temperature in the West, may have had in the fluctuations in streamflow and snow water equivalent (Cayan et al., 2001, Mote et al., 2018). The VIC model timescale covers several oscillations of PDO, from a negative phase from the late 1940s-1976, a positive phase from 1977-1998, and a negative phase from 1999-2012. Positive phases are associated with increased precipitation in the northwest while negative phases are associated with decreased precipitation (Goodrich, 2007). Similarly, summer and fall El Nino events are associated with “dry” winters, and La Nina is associated with “wet” winters (Cayan et al., 1999). The influences of these climate drivers on SWE, temperature, or streamflow were not considered in this analysis but future work would benefit from including an analysis of these effects. Most notably, it would be interesting to note if the variability in peak streamflow or cumulative streamflow analyzed in this study could be explained by ENSO or PDO signals. Further work should increase the number of stream gauges utilized as well as additional variables within the VIC model to increase the reliability of the results. It would also be pertinent to corroborate the VIC SWE values with observed data from snow telemetry sites. The power-estimated model was set up so that any source that produces SWE values could theoretically be plugged in and used to estimate power. The next step in this work would use downscaled climate projections that contain SWE values to estimate power production into the future. Finally, this work builds upon previous studies that connect increasing temperatures to hydrology in the West, but a more complete picture would perform additional analysis regarding temperature changes affecting individual stream gauge regions as well as the watershed as a whole (Pederson et al., 2010, Stewart et al., 2005, Cayan et al., 2001).

It is important to note the many efforts being made to remove the lower Snake River Dams, including the Lower Granite Dam, in an attempt to protect endangered salmon populations from extinction. NOAA (National Oceanographic and Atmospheric Research Center) released a report detailing the continued decline of fish populations, including the effect of habitat fragmentation from dams located along their migration routes (United States, 2022). Earth Economics released a report about the impact the four dams specifically have on fish ecology, energy production, tourism, and the economy as well as the consequences of breaching the dams (LSRD Benefit Replacement Report, 2022). In 2023, Washington State released its budget plans, which include $7 million towards transition planning regarding the transportation, energy, and irrigation services the four dams provide. Additionally, Idaho representative Mike Simpson and tribal representatives have supported the removal of the lower Snake River Dams. In this light, it is helpful to understand the energy services the dams are currently providing, and what we could expect in the coming years. Even without removal, changing water supply and increasing energy demand are reducing the reliability of the dams as power producers.

6. Conclusion

As the West's population exploded in the early 1900s, water was of the utmost concern. Many novels have been written about the feuds and scandals surrounding access to water in one of the world's most populated desert landscapes. And while the Southwest, California, Idaho, Eastern Oregon, and Eastern Washington are all parched for precipitation during the long summers, the Pacific Northwest boasts consistent rainfall and massive rivers channeling water into the Pacific. In the mid-1900s as more energy was needed to secure electricity for the booming population, the engineers chose hydropower. The West was built on hydropower and it has served as the baseload energy supply for decades. However, all the major dams that would have made sense to build, have been built. As the country looks to decarbonize the grid, many pathways look toward expansive solar and wind farms with the role of hydropower shifting from baseload energy supply to supplementary, grid-balancing energy. If this is to be the case, it is important to understand the seasonality of hydropower as a reliable energy source to establish its utility in balancing the grid. The Lower Granite Dam produces very little power in July, August, September, and October because in these months, most if not all of the snowpack has already melted and there are few if any, rainstorms. As the trend in snowmelt continues to occur earlier, we can expect the Lower Granite Dam's drop in energy production to shift earlier, creating a longer period of low production. These months are historically some of the hottest months and they will only continue to warm, likely increasing energy demand for those months as air conditioning needs increase. While solar can be expected to produce power during these dry summer months, a cloudy day when the alternative energy source of hydropower is not producing power would be extremely straining for the energy grid. The 2019 Pacific Northwest Loads and Resources Study, a federal report detailing operational procedures for federally operated energy production in the next decade, already anticipates the region to experience energy deficits due to both decreasing production and increasing demand (Bonneville Power Administration, 2019). The decreasing production results from the entire system being based on hydropower to such an extent that there are no significant enough alternative energy sources to counteract any deficits resulting from dry conditions.

The underlying motivation for this work was to understand how climate change is affecting water supply, and how that may influence energy decisions in the future. This study only focused on hydropower, although in order to fully grasp the intersection of water supply and energy in the West, we need to understand water demand in all land uses, as alternative forms of energy will invariably be built on land that participates in the water cycle, either through the low demand of natural ecosystems or from competitive use for agricultural, industrial, or municipal uses. Further investigation should be done into carbon-free energy sources that are resilient to dry years, such as geothermal, solar, and wind, although each of these sources interacts with the land and water in their own unique way. Those interactions will need to be comprehensively understood in order to make the most effective, informed decisions as we pursue deep decarbonization in the energy grid.

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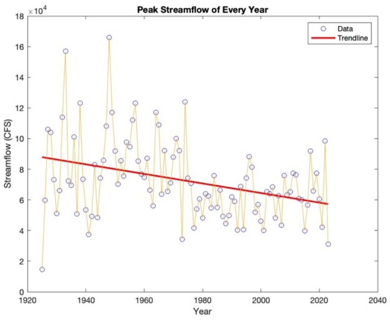
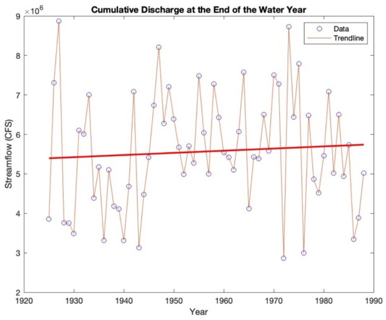
8. Appendix

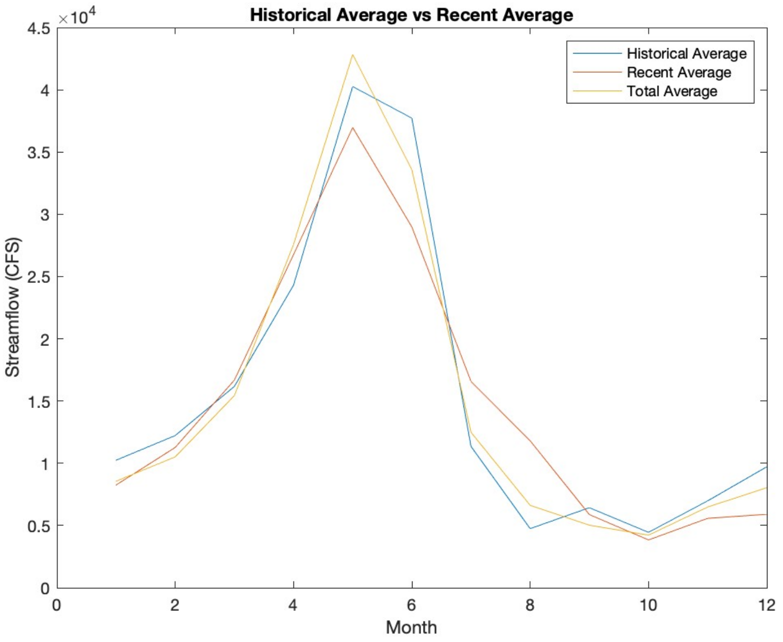
8.1 USGS Stream Gauges

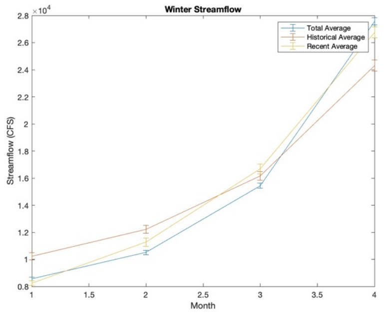
8.1.1 HUC13342500

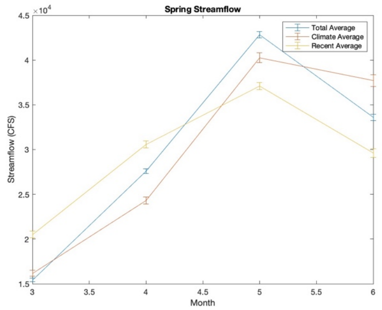
Clearwater River near Spalding, Idaho. The record for this gauge begins in 1925.

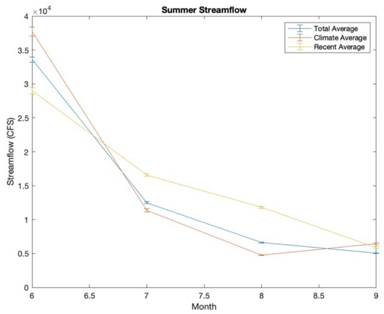

Peak Streamflow of Every Year
×10^4
Data
Trendline
Streamflow (CFS)
Year
0
2
4
6
8
10
12
14
16
18
1920
1940
1960
1980
2000
2020
2040

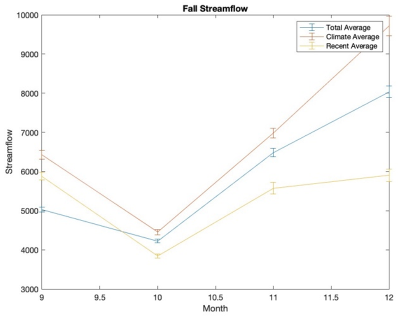

Cumulative Discharge at the End of the Water Year
×10^6
Data
Trendline
Streamflow (CFS)
Year
2
3
4
5
6
7
8
9
1920
1930
1940
1950
1960
1970
1980
1990


Historical Average vs Recent Average
×10^4
Historical Average
Recent Average
Total Average
Streamflow (CFS)
Month
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
2
4
6
8
10
12



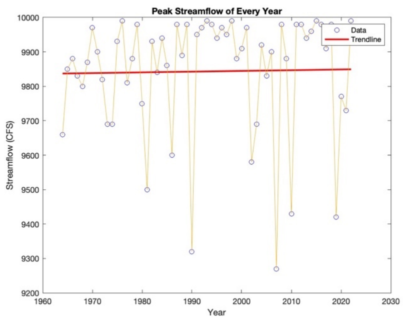


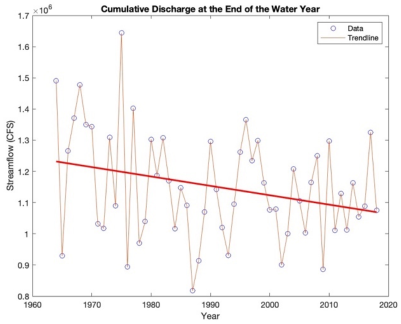


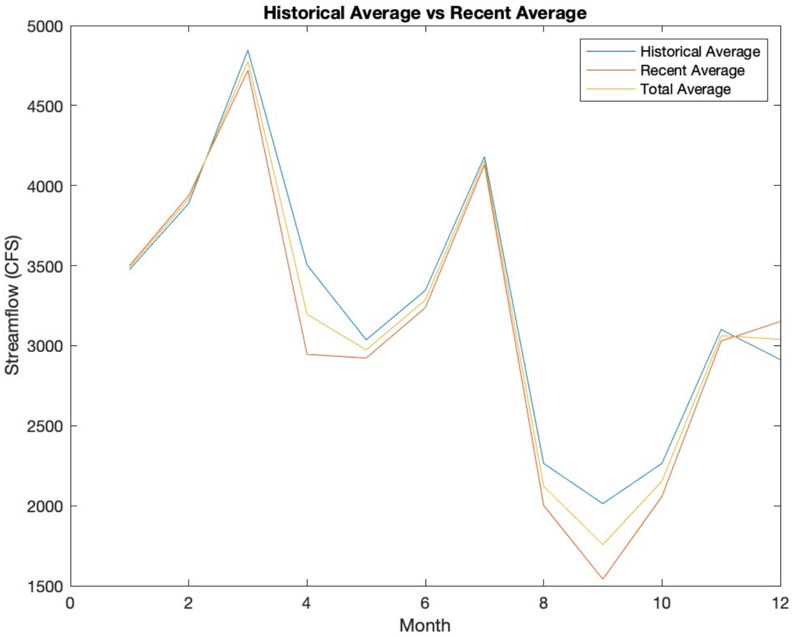


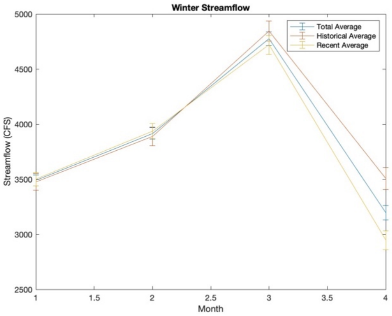
8.1.2 HUC13340000

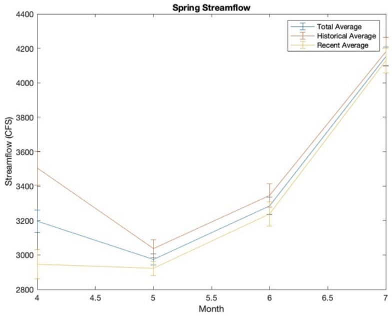
Clearwater River at Orofino, ID. The record for this stream gauge begins in 1963.

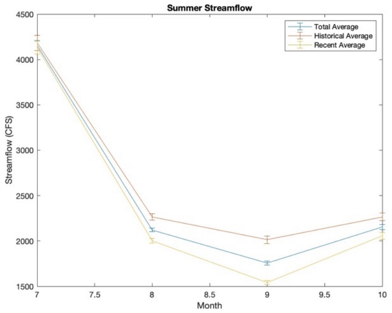


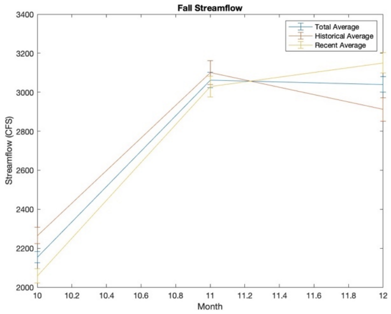



Historical Average vs Recent Average
Historical Average
Recent Average
Total Average
Streamflow (CFS)
5000
4500
4000
3500
3000
2500
2000
1500
0
2
4
6
8
10
12
Month


Winter Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
5000
4500
4000
3500
3000
2500
1
1.5
2
2.5
3
3.5
4
Month

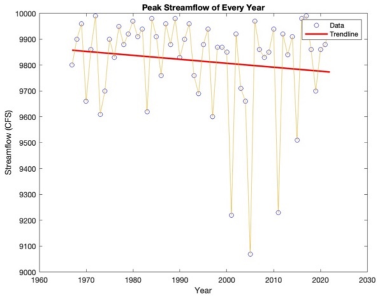

Spring Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
4400
4200
4000
3800
3600
3400
3200
3000
2800
4
4.5
5
5.5
6
6.5
7
Month

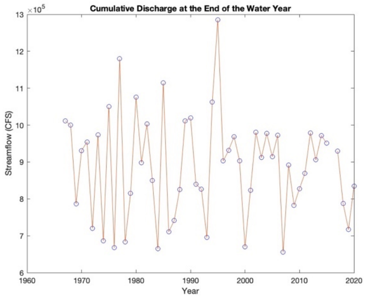


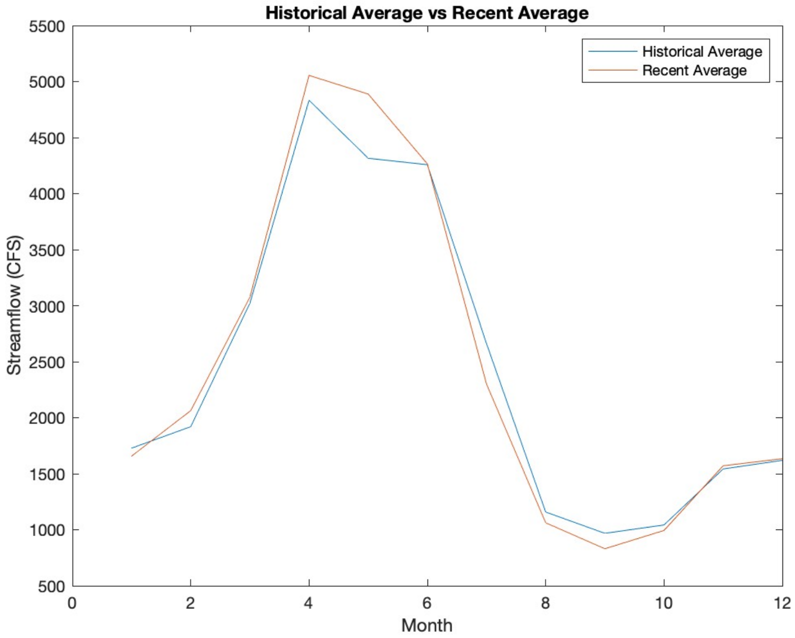


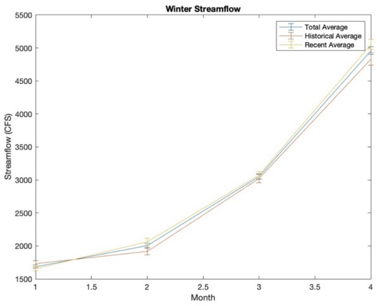
8.1.3 HUC13340600

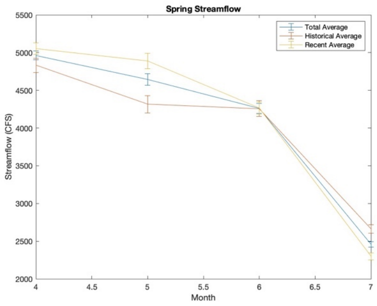
North Fork of the Clearwater River at Canyon Ranger Station. Record for this gauge begins in 1968.

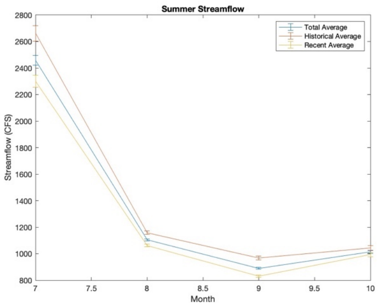


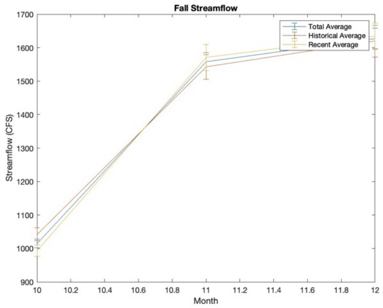



Historical Average vs Recent Average
Historical Average
Recent Average
Streamflow (CFS)
Month
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
2
4
6
8
10
12


Winter Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
Month
5500
5000
4500
4000
3500
3000
2500
2000
1500
1
1.5
2
2.5
3
3.5
4

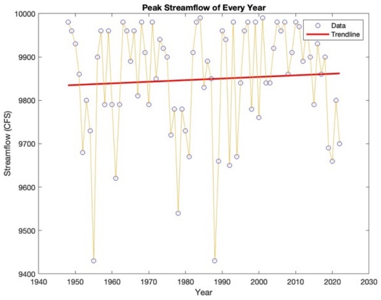

Spring Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
Month
5500
5000
4500
4000
3500
3000
2500
2000
4
4.5
5
5.5
6
6.5
7

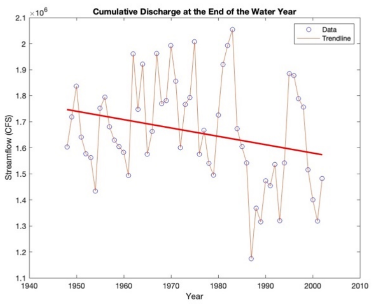


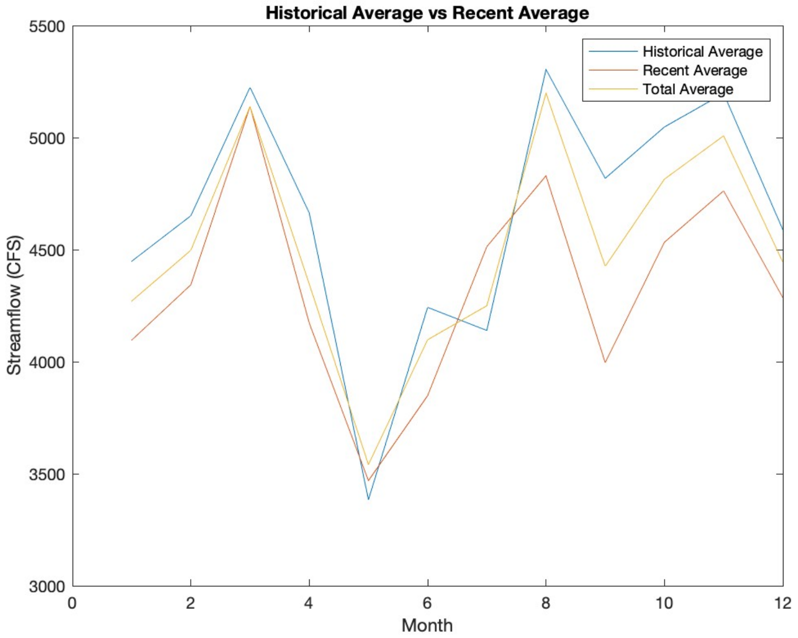


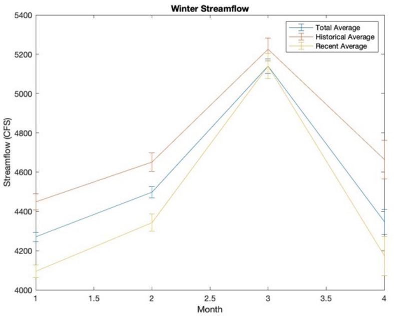
8.1.4 HUC13317000

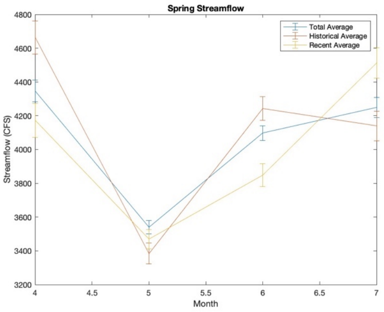
Salmon River at Whitebird, ID. The record for this gauge begins in 1948.

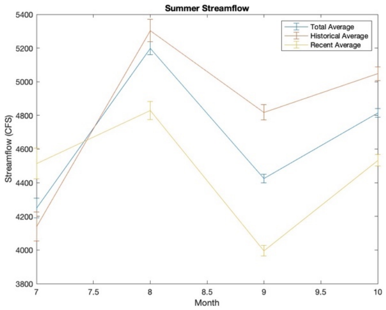


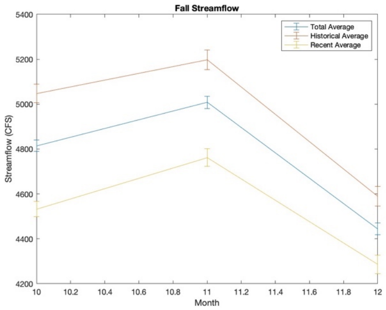



Historical Average vs Recent Average
Historical Average
Recent Average
Total Average
Streamflow (CFS)
Month
5500
5000
4500
4000
3500
3000
0
2
4
6
8
10
12


Winter Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
Month
5400
5200
5000
4800
4600
4400
4200
4000
1
1.5
2
2.5
3
3.5
4

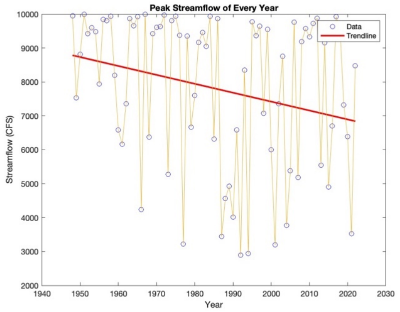

Spring Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
Month
4800
4600
4400
4200
4000
3800
3600
3400
3200
4
4.5
5
5.5
6
6.5
7

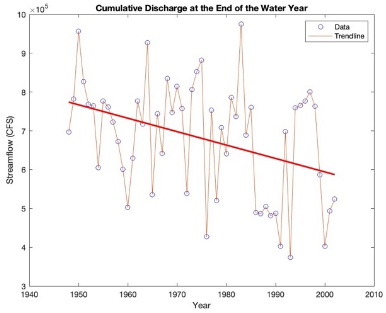


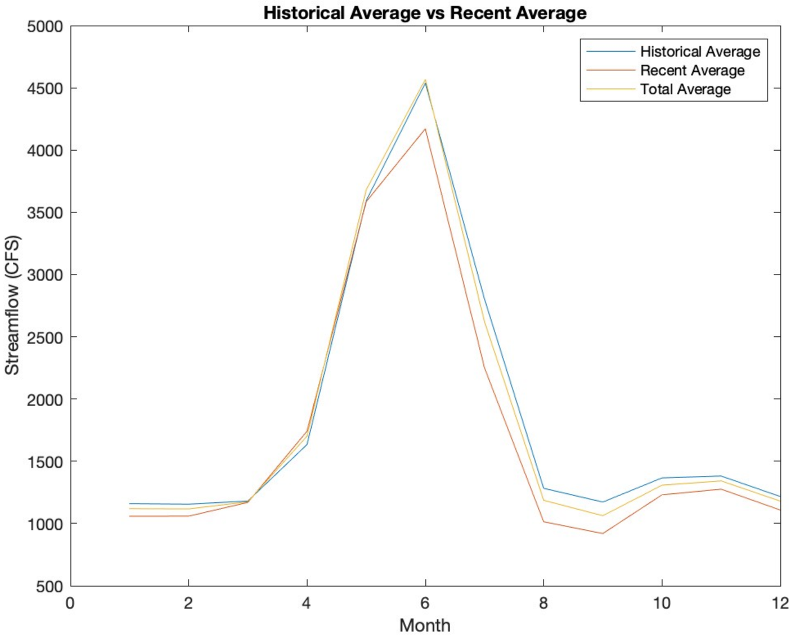


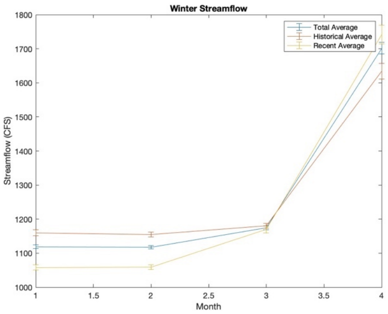
8.1.5: HUC13302500

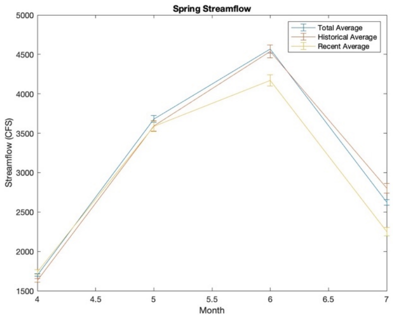
Salmon River at Salmon, ID. Record begins in 1948.

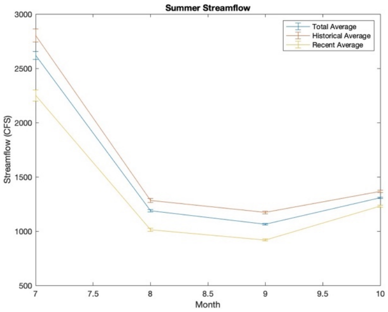


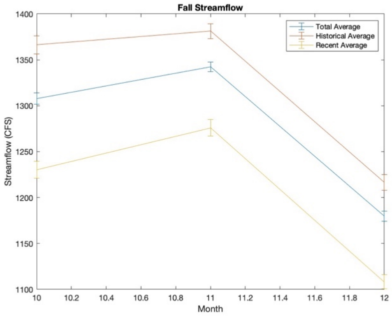



Historical Average vs Recent Average
Historical Average
Recent Average
Total Average
Streamflow (CFS)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
2
4
6
8
10
12
Month


Winter Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
1800
1700
1600
1500
1400
1300
1200
1100
1000
1
1.5
2
2.5
3
3.5
4
Month

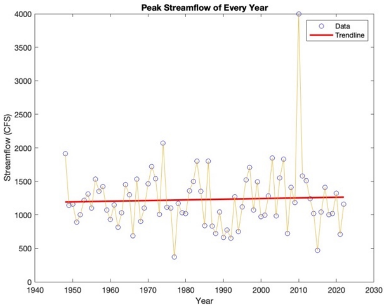

Spring Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
5000
4500
4000
3500
3000
2500
2000
1500
4
4.5
5
5.5
6
6.5
7
Month

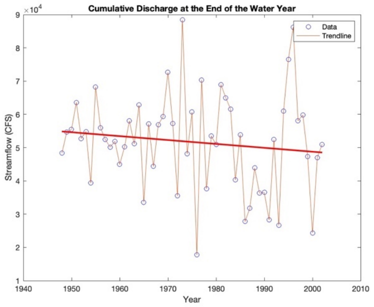


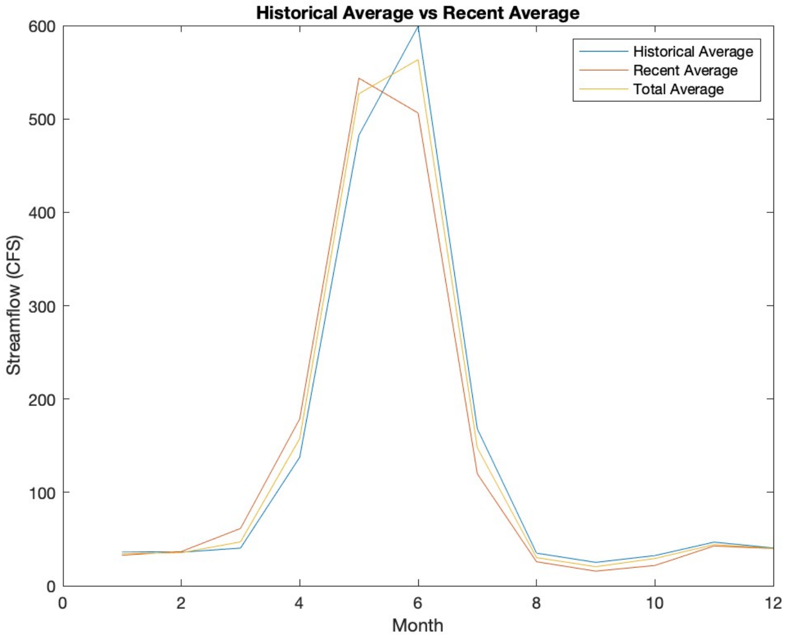


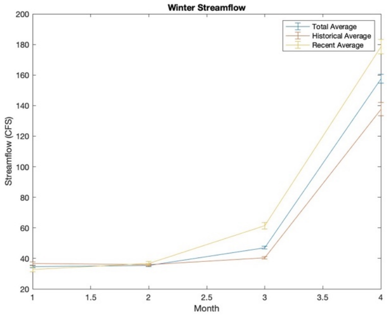
8.1.6 HUC13240000

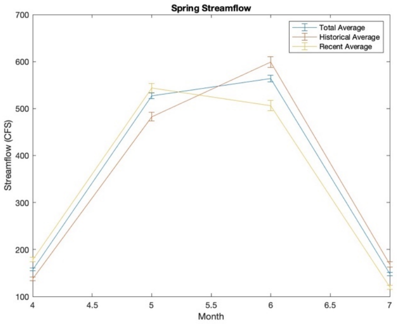
Lake Fork of the Payette River near McCall, ID. This record begins in 1948.

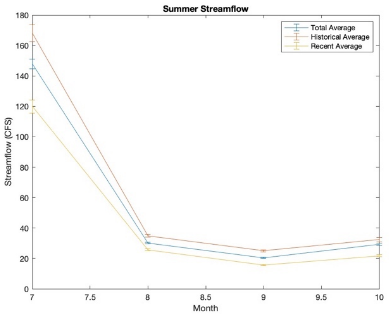


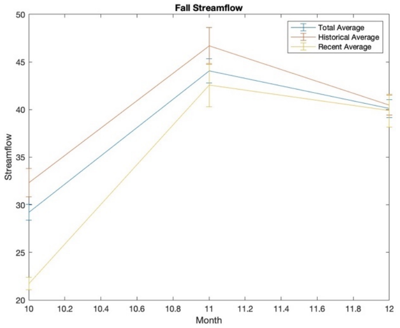



Historical Average vs Recent Average
Historical Average
Recent Average
Total Average
Streamflow (CFS)
600
500
400
300
200
100
0
0
2
4
6
8
10
12
Month


Winter Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
200
180
160
140
120
100
80
60
40
20
1
1.5
2
2.5
3
3.5
4
Month

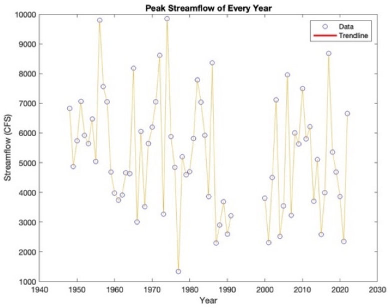

Spring Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
700
600
500
400
300
200
100
4
4.5
5
5.5
6
6.5
7
Month

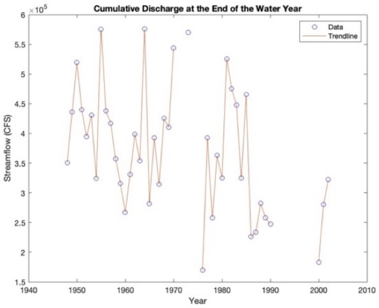


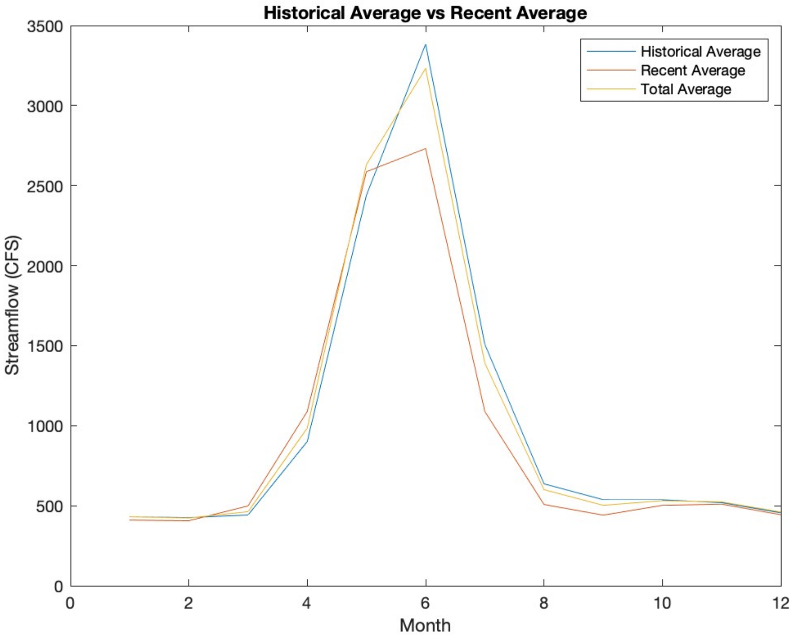


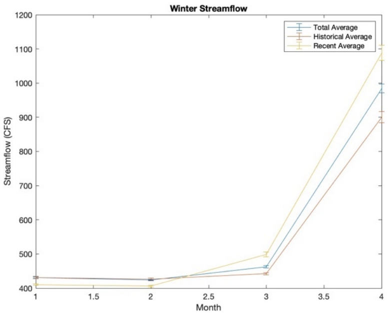
8.1.7 HUC13296500

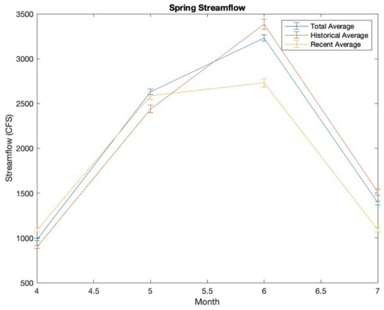
Salmon River below Yankee Fork. This record begins in 1948.

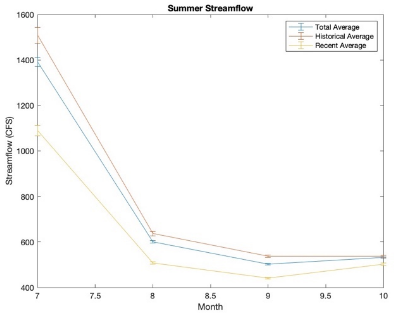


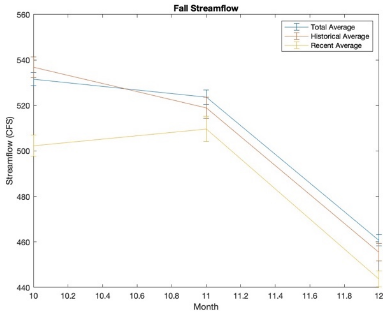



Historical Average vs Recent Average
Historical Average
Recent Average
Total Average
Streamflow (CFS)
Month
0
500
1000
1500
2000
2500
3000
3500
0
2
4
6
8
10
12


Winter Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
Month
400
500
600
700
800
900
1000
1100
1200
1
1.5
2
2.5
3
3.5
4

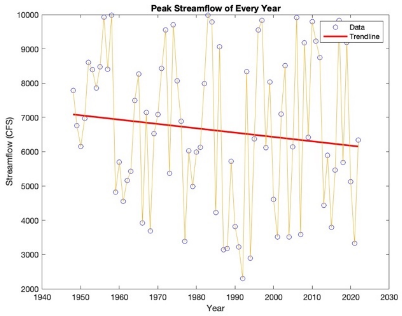

Spring Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
Month
500
1000
1500
2000
2500
3000
3500
4
4.5
5
5.5
6
6.5
7

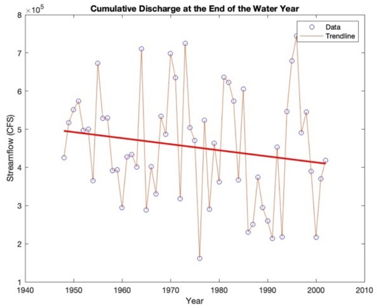


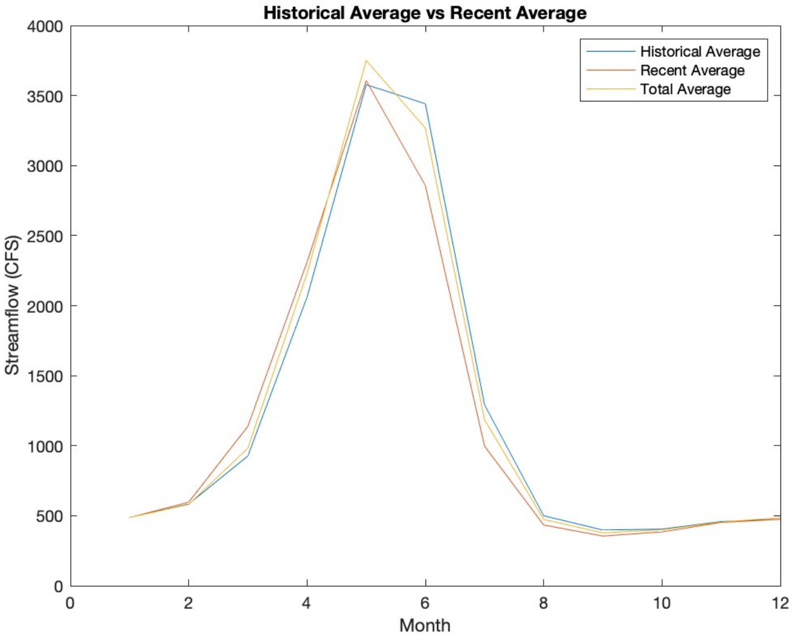


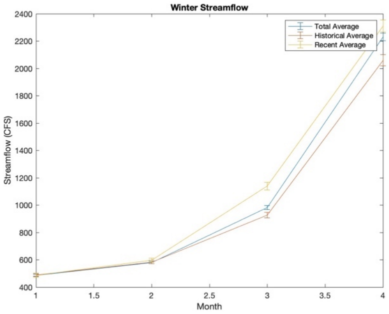
8.1.8 HUC13185000

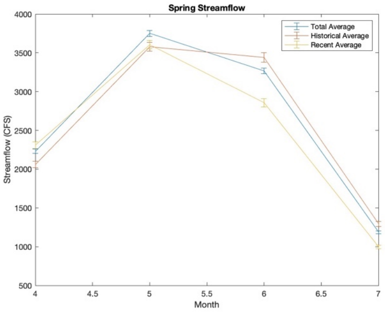
Boise River near Twin Springs, ID. The record for this gauge begins in 1948.

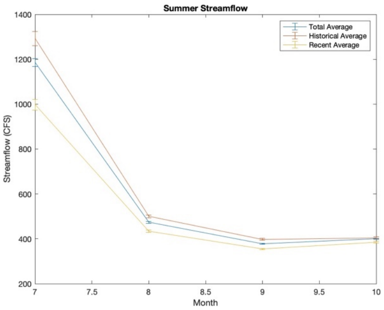


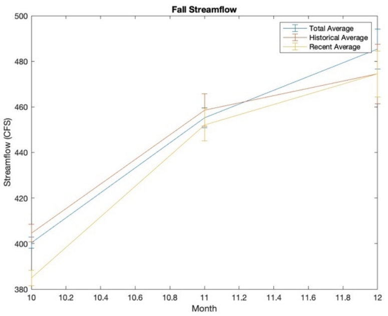



Historical Average vs Recent Average
Historical Average
Recent Average
Total Average
Streamflow (CFS)
0
500
1000
1500
2000
2500
3000
3500
4000
0
2
4
6
8
10
12
Month

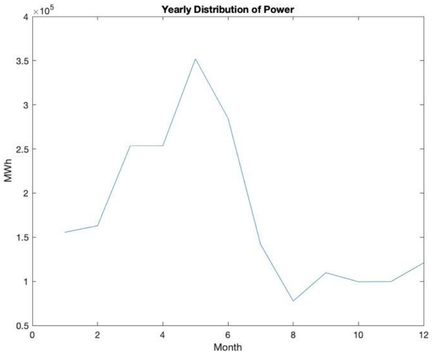

Winter Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
1
1.5
2
2.5
3
3.5
4
Month

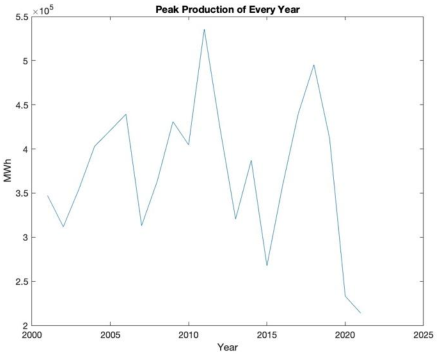

Spring Streamflow
Total Average
Historical Average
Recent Average
Streamflow (CFS)
500
1000
1500
2000
2500
3000
3500
4000
4
4.5
5
5.5
6
6.5
7
Month

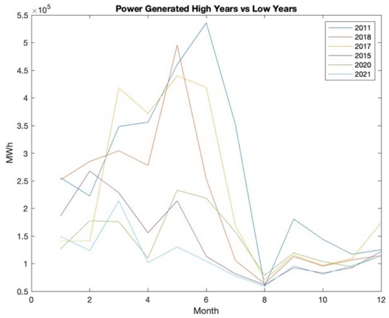


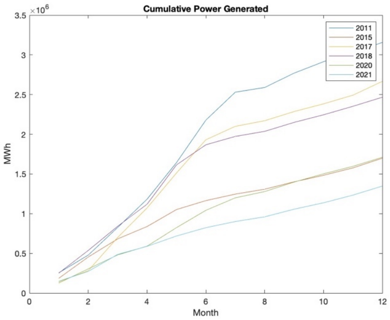


8.2. Power Production

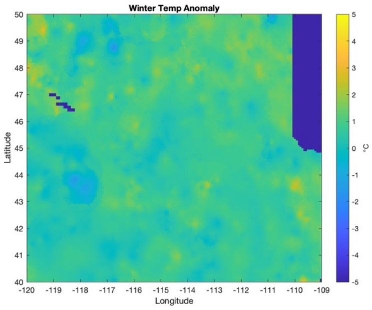


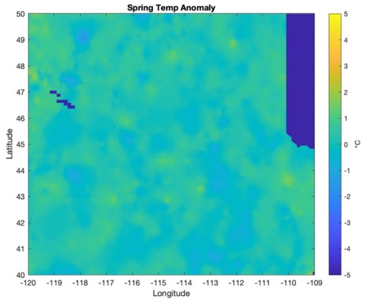


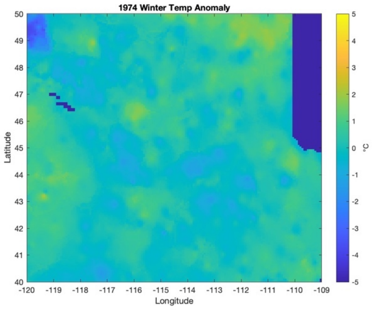


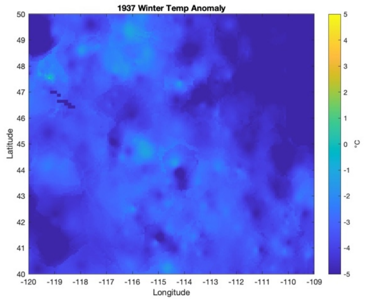


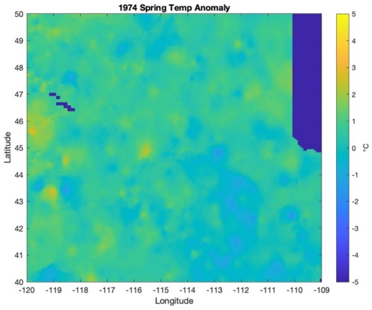
8.3 VIC Temperature Anomaly Images

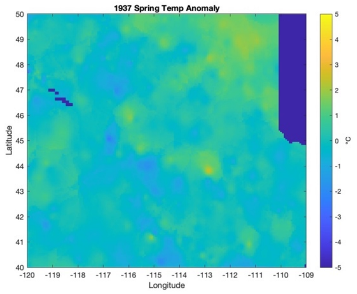

Winter Temp Anomaly


Spring Temp Anomaly

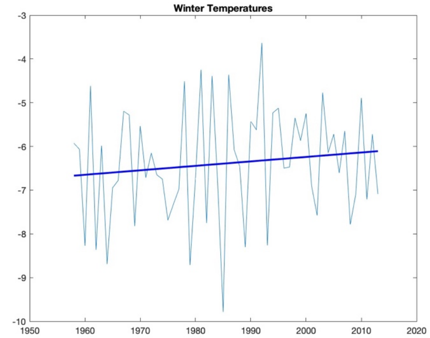

1974 Winter Temp Anomaly

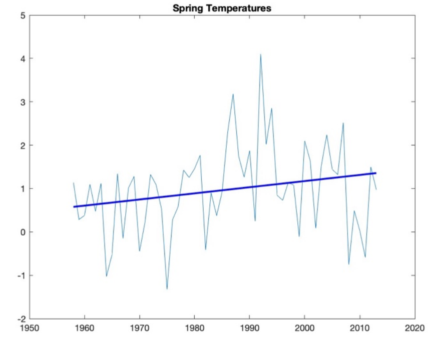

1937 Winter Temp Anomaly


1974 Spring Temp Anomaly

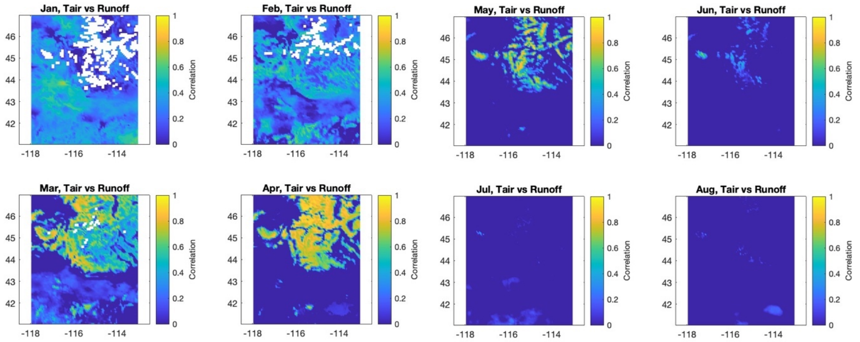

1937 Spring Temp Anomaly

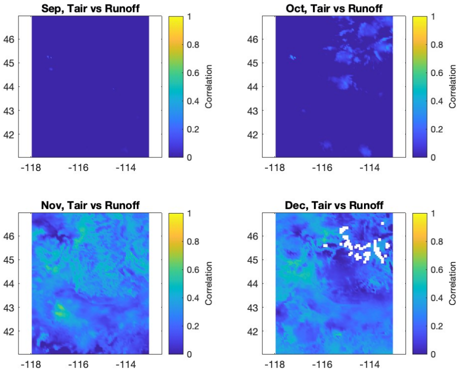
8.4 VIC Estimated Winter and Spring Temperatures





8.5 VIC Air Temperature Correlations with VIC Runoff





8.5 VIC Temperature correlations with HUC13334300 streamflow