

White Salmon River Pre and Post Dam Removal

<https://github.com/kmswann/WhiteSalmon.git>

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1 Rationale and Research Questions

The White Salmon River (White Salmon) is a tributary of the Columbia River in Southern Washington. It provides habitat for at least 5 threatened and endangered fish species and is one of the best white water rivers in the US (Pesanti, 2016). In 1913, a hydroelectric dam, the Condit Dam, was built 3 miles from the mouth of the river (Figure 1: White Salmon River). The dam acted as barrier to salmon species and also to kayakers who paddle both upper reaches of the river and a short section below the dam.

Below hydroelectric dams, the downstream discharge rates – measured in cubic feet per second (cfs) – become altered based on energy production (Grantham et al, 2014). These unnatural flows tend to lower the amount of water in the river during the dry season, as water is conserved in the upstream reservoir for continued energy production. This causes deleterious conditions for salmon habitat (URS, 2005). In 2011, the Condit Dam was removed from the White Salmon. It is assumed that dam removal will benefit salmon through not only having a physical barrier removed but through restoring natural stream flow conditions on the White Salmon River.

This is a multipronged assessment of streamflow trends in the White Salmon pre and post dam removal. I answer the question as to whether flows have changed after dam removal through flood and low flow interval comparisons, Wilcoxon signed-rank test, and seasonal mann kendall time series assessments.

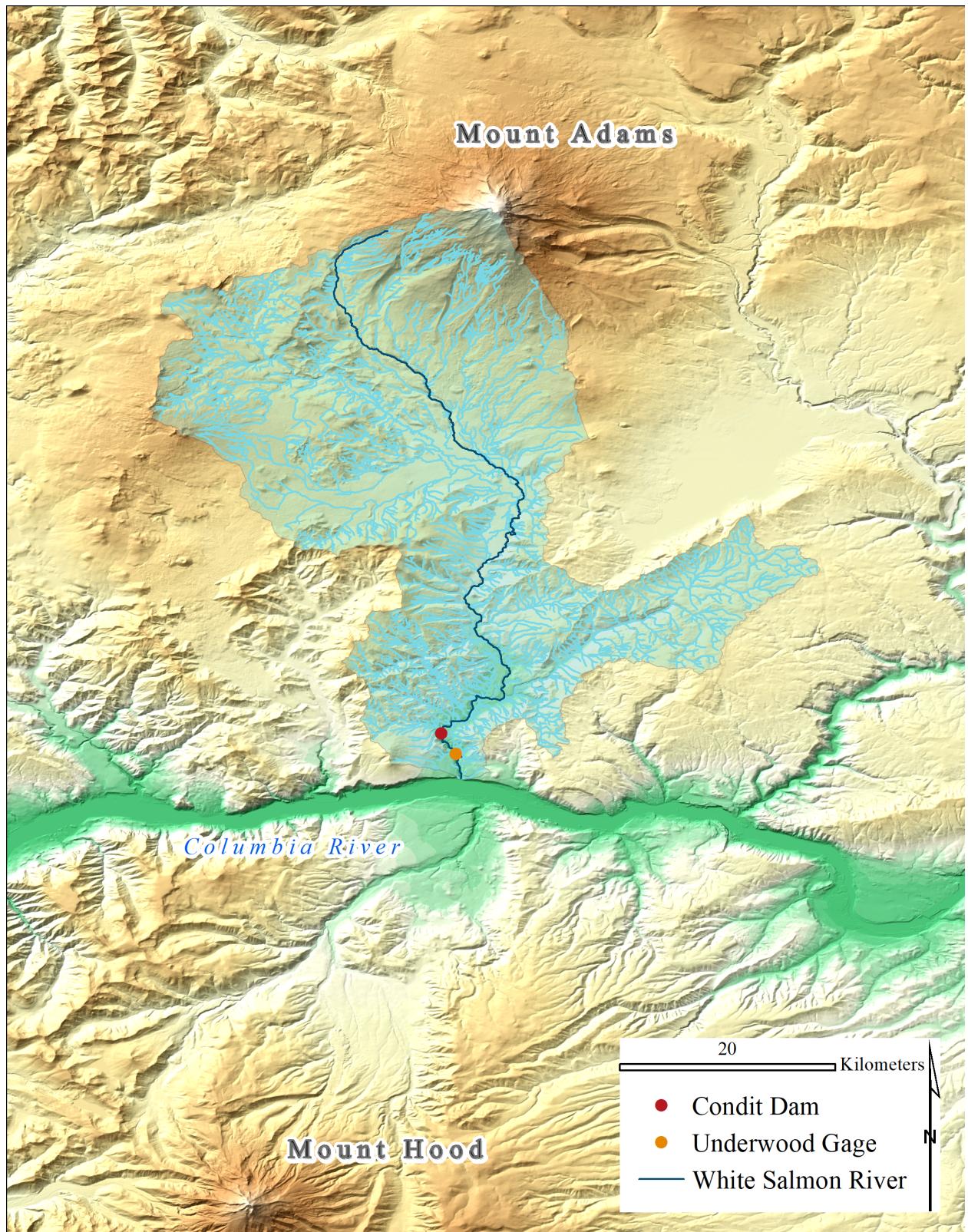


Figure 1: White Salmon River Basin

2 Dataset Information

2.1 USGS Stream Gage Data

Data used here include daily stream flow data for water years 1940-2019. Stream flow data was sourced from a USGS stream gauge station less than one mile downstream of the Condit Dam site (Station ID: 14123500). This station is colloquially referred to as the ‘Underwood Gage’. The data is loaded into R via the dataRetrieval package; a csv of the raw data has been saved in the project folder path ./Data/whitesalmon.csv.

2.1.1 Stream data content information

There are many permutations of the stream gage data that occur through scripts. The raw stream gage data that is the basis for each script file have the following columns:

agency_cd: who created the data (USGS)

site_no: this is the station id (14123500)

Date: %Y-%m-%d

Flow: discharge rate in cubic feet per second

Flow_cd: QA/QC code for discharge data created by USGS

Year: Year pulled from Date

Month: Month pulled from Date

WaterYear: Based on a year of October - September

2.1.2 Stream data wrangling

USGS stream gauge data was rearranged into water years format, which shifts the ‘year’ to be the period between October 1st of one year and September 30th of the following year, with the year designated by the calendar year in which that period ends (i.e. the calendar year for September). The data was split into three groups: - Water Years 1941-2019: Period of record - Water Years 1941 - 2011: Pre dam removal data - Water Years 2012-2019: Post dam removal data - Water Years 2004 - 2011: Pre dam removal data (equal years to post dam removal data) - Water Years 2004-2019: Equal years before and after dam removal. Note that Water year 2012 data was included even though dam removal occurred during this year (October 26).

Not all assessments used all of these water year-based data subsets, but these subsets reflect how time was considered: the overall period of record (1941 to 2019), the historical context pre dam removal (1941 to 2011), post dam removal (2012-2019), and setting equal years pre and post dam removal to remove the weight of long-term trends of dam-management, peak flows and drought. The specific time frames considered are detailed within each analysis.

2.2 Spatial Data

Additional spatial data were used for mapping purposes. The sources of these data are listed below.

USGS

- Basin delineation via StreamStats (streamstats.usgs.gov/ss/)
- Underwood gage latitude and longitude (https://waterdata.usgs.gov/wa/nwis/nwismap/?site_no=14123500&agency_cd=USGS)
- National Hydrography Dataset (NHD) (<https://www.usgs.gov/core-science-systems/ngp/national-hydrography>);

ArcGIS Image Service

- Elevation tinted hillshade basemap
- Condit Dam latitude and longitude (remote sensed via basemap).

3 Exploratory Analysis

Originally, data from 1914 to present day was included (Figure 2). Given the data gap in the mid 1930s, data was parsed to begin on October 1, 1940. Daily data over 78 years results in almost 29,000 days of observations. While QA/QC code from USGS identified several days of estimated flows, these were included within the dataset because estimates can be derived from gage height measurements that exist at this station. The data here are generally positively skewed with outliers – this is expected to occur given flooding recurrence (Figure 3). A log transformation was carried out on monthly data but outliers remained; therefore, it was not used. Major regional flood events are visible in the raw data time series, including a localized flood event in 1974 and the historic flood of 1996. Descriptive statistics subset by time period show that the overall means, medians and various percentiles are relatively similar across subsets but that, as expected, historic data have a lower minimum and higher maximum due to sample size. The 2011-2019 time period has a slightly elevated minimum and slightly lowered maximum as one would expect with less samples, but other percentiles and the median and mean are slightly elevated compared to other periods (Table 1). This points to potential shifts in discharge trends. When the data is further broken down to monthly means by time period, it appears that seasonal shifts are potentially occurring (Figure 4). In particular, late winter to early spring months show increases in mean discharge compared to both historic and recent (2004-2011) data. Without a reservoir storing spring melt, the river seems to be experiencing higher rainy/wet season flow rates. Further statistical tests are carried out below to assess this.

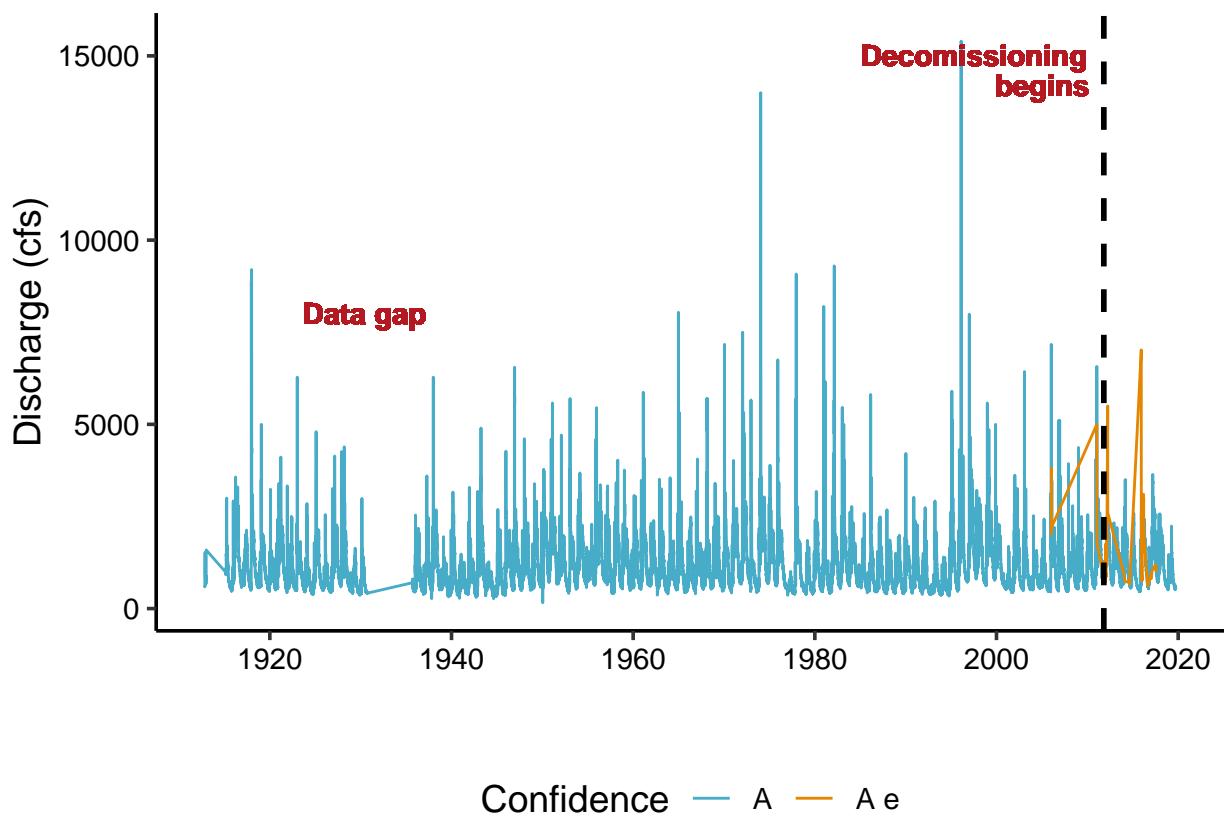


Figure 2: Discharge over time with USGS QA/QC codes

Table 1: Descriptive statistics by period

Statistics	p1940-2019	p2003-2019	p2003-2011	p2011-2019
Min	158.000	454.000	454.000	456.000
10th percentile	534.000	563.000	537.000	597.000
25th percentile	655.000	675.000	630.250	724.000
Median	936.000	956.000	917.000	986.000
Mean	1117.334	1102.946	1059.708	1146.332
75th percentile	1410.000	1360.000	1330.000	1430.000
90th percentile	1890.000	1830.000	1710.000	1950.000
Max	15400.000	7170.000	7170.000	7020.000

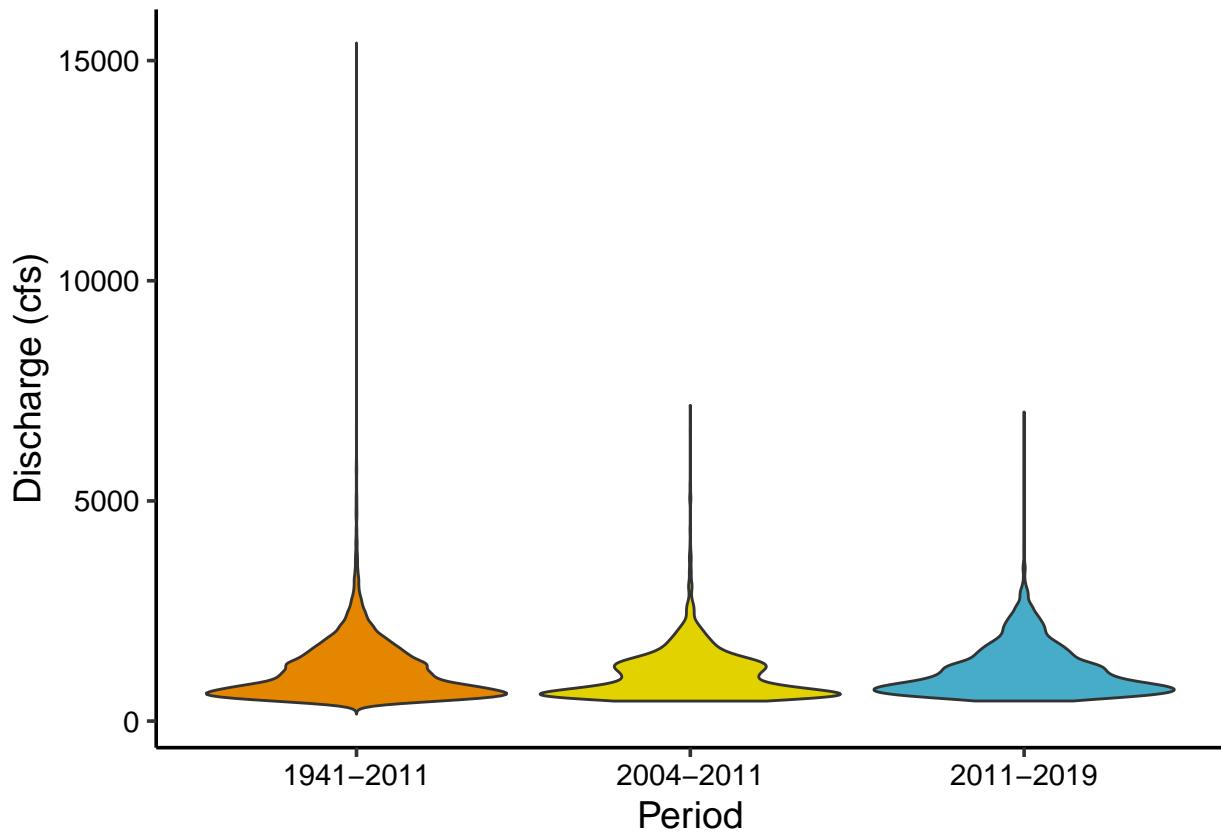


Figure 3: Discharge during different periods on the White Salmon River.

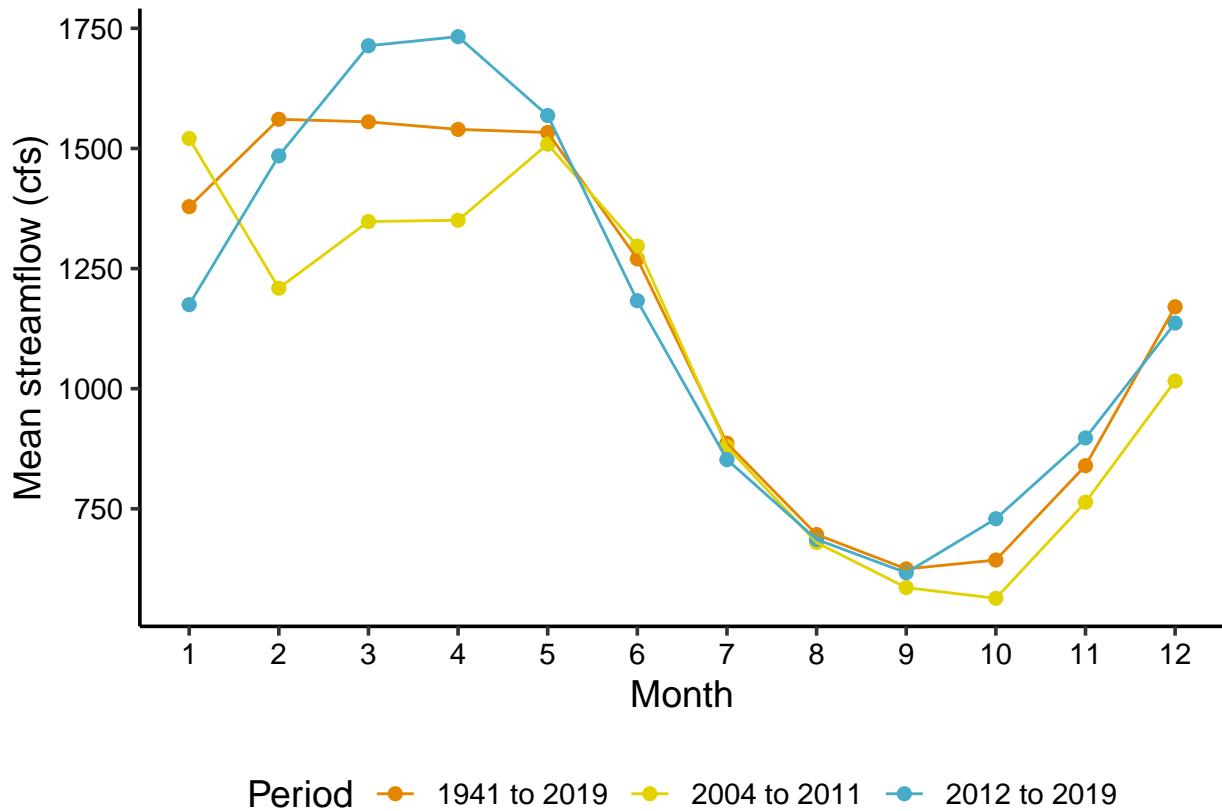


Figure 4: Monthly averages by period.

4 Analysis

4.1 Question 1: Have peak flows changed since the Condit dam was removed?

Flood return intervals were modeled based on the period of record discharge data (1941-2019). Return intervals for the 2004-2011 and 2012-2019 water years were then created to compare peak discharge estimates for given intervals (100, 200, 500 and 1,000 year flood return intervals). The 2004-2011 period was used to visualize pre-dam removal conditions in the years leading up to the dam removal. The 2004-2011 period was included in order to visually assess if there were dramatic differences in flood regimes in the years leading up to the dam removal. The rationale for needing this visualization is that there could have been either basin level land-use changes, precipitation changes, or, most importantly, dam release changes that could have materialized in recent years compared to the historic trends from the 1940s. Looking at such a short period also removes peak events from the dataset. Given that there were no major flood events from 2004-2019, the 2004-2019 visualization is almost functioning as a ‘reference condition’ by which to judge the 2011-2019 model (although given annual fluctuations in precipitation, there is no true ‘reference condition’).

Flood return intervals were created by parsing and ranking annual peak flows from the datasets, followed by dividing the number of years by the ranked peaks. The annual probability associated with these return intervals was calculated. The logged return interval values were then put into a linear model against the peak flows for each period. Using these linear models, estimates for the 100, 200, 500 and 1,000 year flood return intervals were calculated using the predict function. As a reference, the 100 year flood return interval based on the period of record is 14,386 cfs.

The results of these models show that estimated return intervals after the Condit Dam was removed range from approximately 1,700 to 2,500 cfs lower than the period of record estimates (Figure 5, Table 2). Similarly, the return intervals after dam removal are range from approximately 1,200 to 1,600 cfs lower than the 2004-2011 period estimates. These results suggest that annual peak flows are lower now that the Condit Dam has been removed. Recall in Figure 4 that monthly averages during the rainy season appeared to be higher. This could suggest that flows are more consistently high during the rainy seasons, with less incidences of dam-release-related peaks. However, there are a few major caveats here. The largest problem with this assessment is that the linear model for the return intervals for 2004-2011 and 2011-2019 are based on only 8 sample points (annual peaks) each. This is reflected in Table 2, which shows the combined period of 2004-2019 as having overall much lower return intervals than the stand alone periods of 2004-2011 and 2012-2019. More years of data are needed in order to adequately model for the changes in flood regimes, but for now, this is an interesting glimpse into potential patterns.

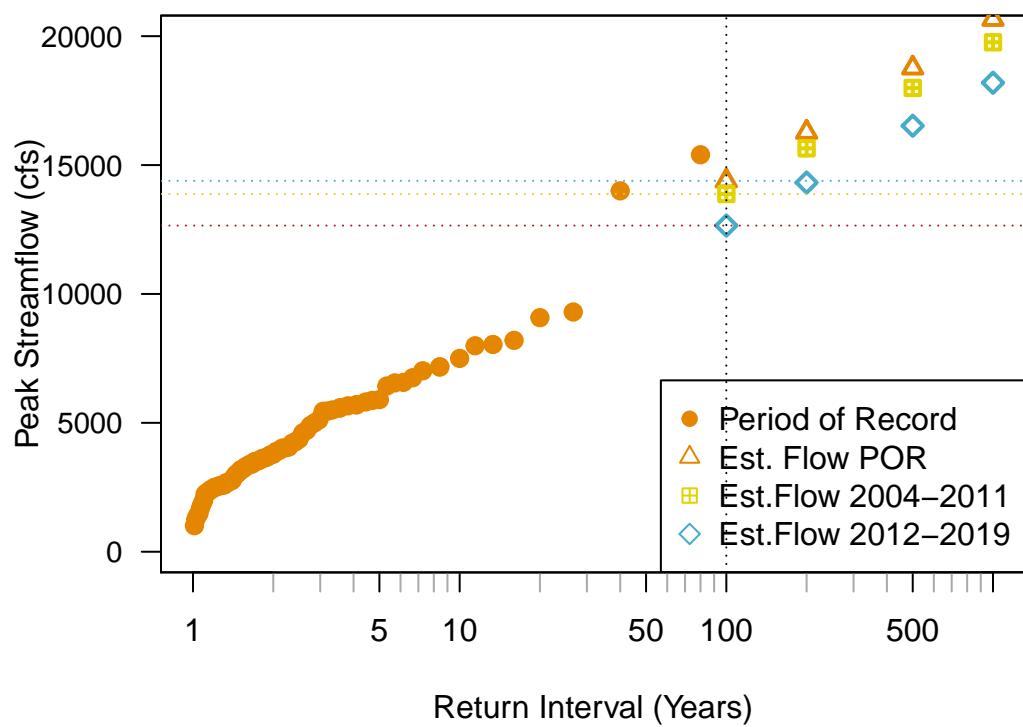


Figure 5: Flood return intervals modeled by period.

Table 2: Flood reutrn intervals modeled by period.

Date Range	RI (100yr)	RI (500yr)	RI (1000yr)	No years	Adjusted R2
1941-2019	14385.82	18767.23	20654.21	79	0.9649911
2004-2019	11993.16	15479.37	16980.81	16	0.9394817
2004-2011	13876.35	17991.03	19763.13	8	0.9379948
2012-2019	12653.76	16524.85	18192.03	8	0.9561816

4.2 Question 2: Have low flows changed since the Condit dam was removed?

The lowest 7-day average flow that occurred annually was calculated for the period of record and the post-dam period. This is referred to as the minimum Q7. The return intervals and annual probabilities were again calculated from these parsed values. Unlike the flood return intervals, in this case, the 7Q10 is the lowest 7-day average discharge that occurs every 10 years. This 7Q10 value is a standard management metric for low flows (EPA, 2018). The 7Q10 based on the period of record is 405 cfs, whereas the 7Q10 for the 2012-2019 period is 452 cfs (Figure 6, Table 3). These calculations are once again based on linear models, in this case using the minimum Q7 values against annual probabilities and then using the predict function to find estimates for the annual probability of exceeding the 7Q10.

For brevity sake, only the period of record and post dam removal period were considered. The model shows that post dam removal low flows are higher than the historic low flows, which when applied to point of record daily discharge means, shows a substantial difference in number of days of low flows (Figure 6, Table 3). This suggests that the natural low flows in the White Salmon River below Condit Dam could have been historically much higher prior to dam construction. The dam could have been having significant ecological impacts that were simply not perceived because the age of the structure predates the use of the 7Q10 for river management. Alternatively, again, the data being used to model the 7Q10 since dam removal is limited. There is a need for more years of data.

Table 3: 7Q10s on the White Salmon River. Note that the number of years are the years where flows occur at or below 7Q10 within the entire period of record based on the 7Q10 for the given period.

Date Range	7Q10 (cfs)	No Years	Annual Prob	Adjusted R2
1941-2019	408.85	21	26.25	0.89
2012-2019	451.66	30	37.50	0.93

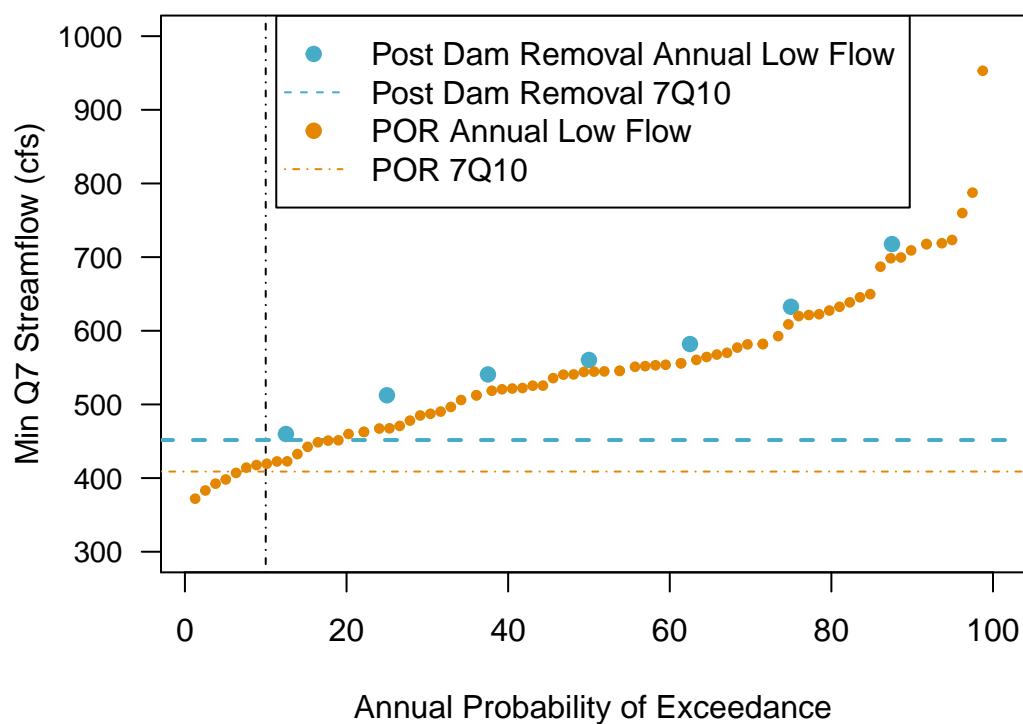


Figure 6: Annual probability of exceeding the minimum Q7.

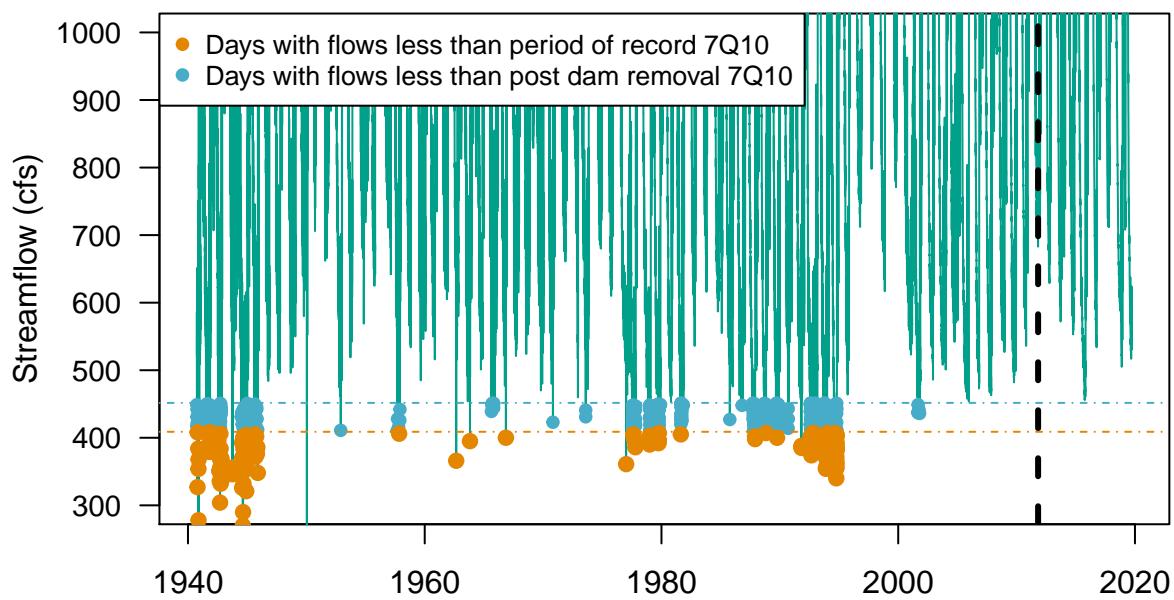


Figure 7: The number of low flow days in the White Salmon River based on the period of record and post dam removal period.

4.3 Question 3: Is there a significant difference between historic and recent conditions and post-dam removal conditions?

A Wilcoxon rank sum test was run on the historic and post-dam removal datasets. A Welch's two sample t-test was run on the recent (2004-2011) data and post-dam removal data. The choices to run these tests were based on meeting assumptions associated with the compared datasets. The Shapiro-Wilk normality tests all showed that these datasets do not have normal distributions, as expected (p -values < 0.0001). An F-test to compare two variances between historic and post dam removal data showed the variances of the two datasets to be equal ($F=1.41$, $df = 25931$, p -value < 0.0001). This led to using the Wilcoxon rank sum test on these samples. The F-test to compare variances between recent and post dam removal data showed the variances of the two datasets to be unequal ($F=1.02$; $df = 2921$, p -value = 0.64). This led to the use of Welch's t-test.

The results of these tests both showed the means and medians of the compared samples to be significantly different (historic and post-dam removal: Wilcoxon test, $W = 35989876$, p -value < 0.0001 ; recent and post-dam removal: Welch's t-test, $t = -5.78$, p -value < 0.0001). Based on these tests, the discharge rates in the White Salmon River are significantly different since the Condit Dam has been removed - regardless of whether one looks at the historic data or the more recent data (2004-2011) in comparison to post-dam removal conditions. This is surprising given the violin plots in Figure 3, particularly for the 2004-2011 and 2011-2019 periods which look very similar.

4.4 Question 4: Are seasonal trends becoming more or less monotonic since the dam was removed?

The Mann Kendall (MK) test is a non-parametric time series regression. It does not require normal distribution, but it does require independence of measurements. While it can be used with daily data, it is more appropriately used, as done here, with monthly data to assure that there is no serial correlation over time. Other assumptions for Mann Kendall regressions include: true conditions, consistently collected data (no gaps), and unbiased methods of measurement. Therefore, it seems that all assumptions have been met for the MK tests. The White Salmon was not expected to have significantly monotonic trends; rather, the hypothesis here was that post dam conditions will be less monotonic than pre-dam conditions. A higher p -value is used to affirm this hypothesis. These tests were run on monthly data for two time frames: 1966-2018 and 2004-2018. The results are broken up in two ways: overall MK test results for given time period and seasonal (monthly) MK test results for given time periods.

4.4.1 Overall MK test results

Seasonal discharge rates were historically monotonic, and even the time period of 2004-2011 had significantly monotonic seasonal discharge rates (historic: $z = -4.33$, p -value < 0.0001 , seasonal Sen's slope = -1.46; recent pre-dam removal: $z = 4.75$, p -value < 0.0001 , seasonal Sen's slope = 41.60). Conversely, there are no significant monotonic trends since the Condit dam was removed (post-dam removal: $z = -1.23$, p -value = 0.218). Note that the Sen's slopes associated with historic and 2004-2011 data show very different magnitudes of trends. Historic

data shows monotonic decrease in seasonal discharges of -1.46 cfs, whereas the 2004-2011 data shows a seasonal increase of 41.60 cfs per year. The overall importance of these MK tests was to assess how post-dam conditions have changed, and the one conclusion that can be made is that monotonic trends have disappeared since the dam was removed. There is a major caveat here that assessing seasonal trends on an 8 year basis may not include enough data to provide reliable statistical results. The test results from these three different time periods may be an artifact of this dilemma. The historic MK test results are likely more dependable given the extent of the dataframe. More years of data are needed to assess post-dam removal conditions.

4.4.2 Seasonal MK test results

The purpose of looking at MK test results for individual seasons was to assess which seasons are seeing more/less monotonic trends based on the p-values of these individual tests. Because the 2004-2011 data seems potentially flawed due to its smaller sample size, I am only going to look at the post-dam removal results compared to the historic results. The results show that every month had less monotonic trends than the historic data. Note that the post-dam removal results also come from a smaller sample size; what these results signify are a glimpse of trends so far. More years of data are needed for these tests to be reliable. Even with the flaws in the datasets sizes, some additional visualizations of monthly averages are included here with LOESS curves in order to visualize the range in monthly values within these three different datasets (Figures 8 and 9). These figures mimic the p-values seen in the seasonal results, which overall show the ranges in discharge to be more narrow in late summer to early fall, and winter to spring flows to have much higher ranges. In Figure 9, it appears that February through July have experienced greater vacillation between low and high monthly averages in discharge when compared annually. It is still early, but the overall picture painted here is that without the dam being present, there is no set minimum or maximum flow that is enforced by humans. The river appears to be pulsing more naturally. More years of data will be needed to assess the impact of dam removal.

There is a more complex story than expected when individual seasons for these MK test results are reviewed. The historic data showed significant monotonic trends for the months of September ($S = -385$, p-value = 0.06) and October ($S = -439$, p-value = 0.03) - late fall before the rainy season begins. The 2004-2011 data showed near significant monotonic trends for the months of May ($S = 15$, p-value = 0.06) and June ($S = 16$, p-value = 0.06) - the beginning of the dry season. The historic data, again, is more reliable given the dataset's size. That September and October saw annual decreases in seasonal discharge rates suggests potentially drier conditions later into winter. This could be caused by climate change, or alternatively, it could be the result of dam management practices shifting over time. Practices that could have shifted include: drawing down the reservoir behind Condit dam earlier in the season in order to make room for a higher volume of winter flows (thus preventing infrastructure damage from high flows), or holding water back later in fall due to a lack of precipitation (thus allowing the dam to continue to produce electricity until the rainy season begins). Assessing this trend would require modeling precipitation trends within the basin.

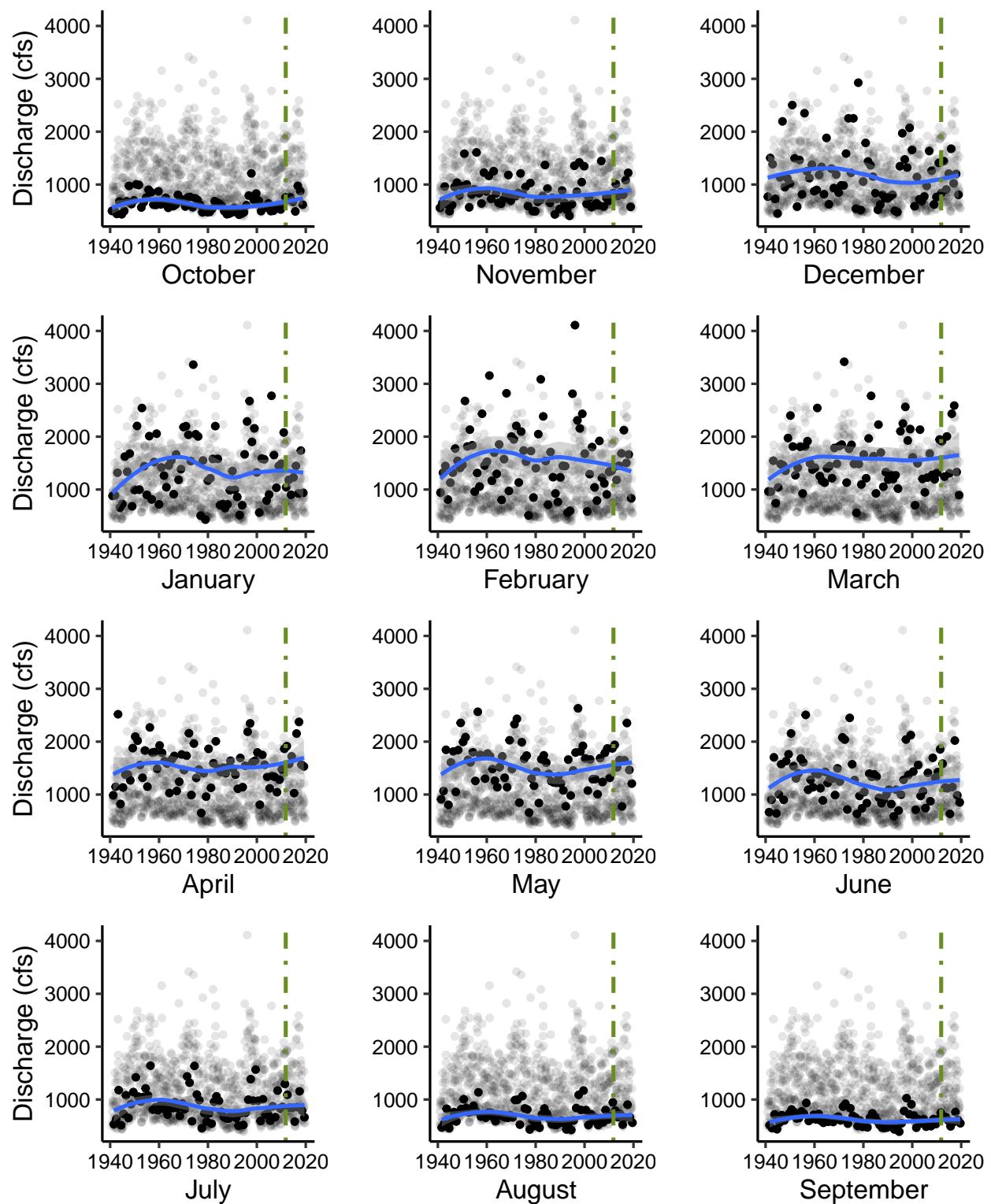


Figure 8: Monthly LOESS curve fit to historic data (1941-2019 water years) on the White Salmon River. Vertical dashed line signifies Condit Dam removal.

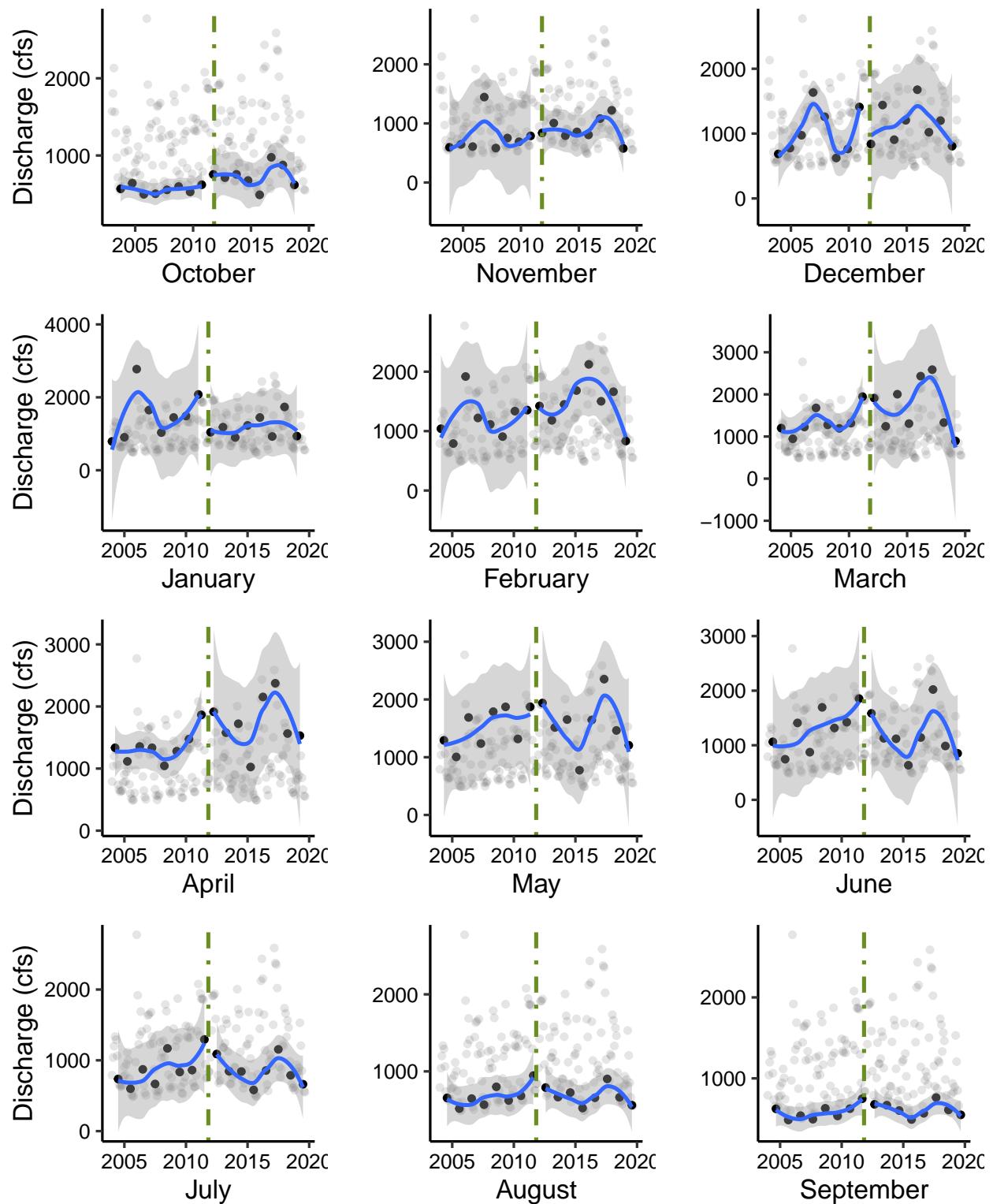


Figure 9: Monthly LOESS curve fit to 2004-2011 and 2012-2019 water years on the White Salmon River. Vertical dashed line signifies Condit Dam removal.

5 Summary and Conclusions

There is a significant difference between flow rates on the White Salmon for the given time periods reviewed here. Since the Condit Dam was removed, low flow rates are modeled via 7Q10 to have increased in value, peak flow rates are modeled via flood return interval to have decreased in value, and overall flow trends are not monotonic. The implications here are that there seems to be a trend of higher low flows and lower high flows, both of which will benefit salmon migration and the food web that salmon depend on. It is likely that low flow rates were kept artificially low due to dam management, especially in the early years of the dam. High flow rates similarly may have been a product of dam management, with peak flows being more pronounced due to peak electricity demand. The switch from monotonic to non-monotonic trends is likely a product of the freeing of the river. All of these conclusions however are limited by the years of data available since dam removal. More years of data are needed.

6 References

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