

Elwha River Dam Removal

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Contents

I. Introduction	4
II. Dataset Information	6
II.A. Streamflow Data	6
II.B. Sediment Data	7
II.C. Water Quality Data	7
II.D. Salmon Diet Data	8
III. Exploratory Analysis	9
III.A. Streamflow	9
III.B. Sediment	11
III.C. Water Quality	13
III.D. Salmon Diet	15
IV. Analysis	16
IV.A. Question 1. How are river discharge and gage height impacted by dam removal?	16
IV.B. Question 2. Is there a significant impact on sediment load and concentration following dam removal?	17
IV.C. Question 3. Is water quality and nutrient availability impacted by the dam removal?	19
IV.D. Question 4. Is there a shift in the types of taxa consumed by salmon before and after the dam removal?	21
V. Summary and Conclusions	26
VI. Appendix	27
VI.A. Data Sources	27
VI.B. References	27

List of Tables

1	USGS Continuous Gage Height Raw Data	7
2	Daily Sediment Concentration and Load Raw Data	7
3	Daily Sediment Concentration and Load Raw Data	8
4	Daily Sediment Concentration and Load Raw Data	8
5	Availability of USGS Streamflow Data	9
6	Selected rocessed data for Chinook salmon diet	15
7	Mann Kendall Test of Streamflow Data - USGS Site 12045500	17
8	Suspended Sediment Concentration (mg/L) During and After Dam Removal	17

List of Figures

1	Elwha Dam approximately one month into removal (NPS, 2025)	4
2	Glines Canyon Dam approximately one month into removal (NPS, 2025)	4
3	Elwha River watershed, monitoring stations, and dam locations (USGS, 2011)	6
4	Elwha River Daily Average Discharge at USGS Site 12045500 (2008–2017)	9
5	Elwha River Daily Average Gage Height (2008–2017)	10
6	Distribution of Daily Suspended Sediment Concentration and Load at USGS Site 12046260 (2011–2016)	11
7	Trends in Daily Sediment Load and Concentration at USGS Site 12046260 (2011–2016) . . .	12
8	Measured nitrate/nitrile concentration [uM] before and after dam removal	13
9	Water quality parameters not selected for further analysis	14
10	Discharge and Gage Height Decomposed Time Series	16
11	Distribution of Sediment Concentration During and After Dam Removal at USGS Site 12046260 (2011–2016)	18
12	Water quality in the Elwha River estuary before and during dam removal	20
13	Total counts of the 10 most common dietary taxa each year in Chinook salmon	22
14	Total counts of the 10 most common dietary taxa each year in Coho salmon	23
15	Top taxa for Chinook and Coho salmon before and during dam removal	24
16	Top taxa for Chinook salmon during dam removal	25

I. Introduction

The Elwha River in Washington was the site of one of the largest dam removal projects in United States history. Headwatered in the Olympic Mountains of Washington and flowing to the Strait of Juan de Fuca, the Elwha River originally supported all five Pacific salmon species, steelhead, and other fish populations, along with the Lower Elwha Klallam Tribe. However, the Elwha Dam and Glines Canyon Dam, located 7.9 km and 21.6 km from the river mouth, respectively, blocked fish and sediment passage for more than 100 years (**Figures 1 and 2**).



Figure 1: Elwha Dam approximately one month into removal (NPS, 2025)



Figure 2: Glines Canyon Dam approximately one month into removal (NPS, 2025)

Alongside the concern for fish populations and ecological balance was the concern of rising sea level and the impacts that dams have on coastal erosion and resilience. To restore the passage of fish, preserve the watershed, and protect the people, the Lower Elwha Klallam Tribe sought to remove the dams. They were instrumental in the passing of the Elwha River Ecosystem and Fisheries Restoration Act in 1992, but it took 20 years for dam removal to begin. Finally, from 2011 to 2014, the two dams were removed and impacts were tracked by a team of federal, state, tribal, academic, and community partners. The lower Elwha Dam was fully removed by Spring 2012, and the upper Glines Canyon Dam was removed by August 2014.

Studies were conducted before, during, and after dam removal to understand the shifts in the geomorphology, hydrology, and ecology caused by the removal. Various groups sought to characterize phenomena such as

sediment and woody debris dispersion, vegetation growth, invertebrate densities, and fish migration. In this study, we sought to analyze a portion of these impacts and specifically focused on the impacts on streamflow, sediment transport, water quality, and fish diet before, during, and after the dam removal.

The experimental questions of this study are as follows:

- Question 1: How are river discharge and gage height impacted by dam removal?
- Question 2: Is there an observable impact on sediment load and concentration following dam removal?
- Question 3: Is water quality and nutrient availability impacted by the dam removal?
- Question 4: Is there a shift in the types of taxa consumed by Chinook and Coho salmon following dam removal?

II. Dataset Information

We have obtained multiple datasets from the United States Geological Survey (USGS) in regards to the Elwha River dam removals. **For more information on data availability and sources, see Appendix.** These datasets include:

1. Elwha River continuous gage height and discharge levels before, during, and after removal
2. Elwha River daily sediment loads and concentrations during and after dam removal
3. Elwha River water quality at the estuary
4. Chinook and Coho salmon diets, sampled at estuary sites

The relative locations of the Elwha River watershed, communities, USGS monitoring sites, and Elwha and Glines Canyon Dams are depicted in **Figure 3** (map sourced from “Coastal Habitats of the Elwha River, Washington-Biological and Physical Patterns and Processes Prior to Dam Removal”, USGS, 2011).

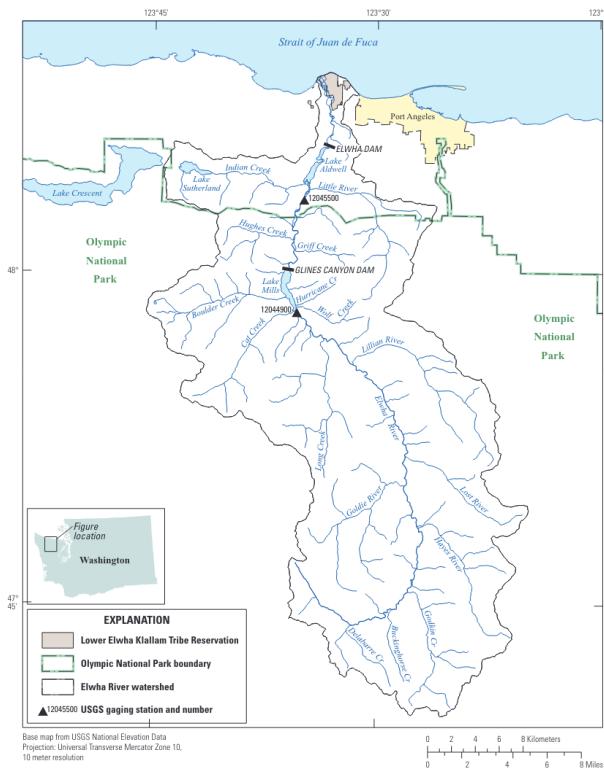


Figure 3: Elwha River watershed, monitoring stations, and dam locations (USGS, 2011)

II.A. Streamflow Data

We obtained continuous gage height and discharge data along the Elwha River from USGS's Water Data for the Nation at several USGS monitoring stations along the Elwha River. Data availability for each monitoring station is discussed in-depth in **Section III.A** below.

Through USGS Water Data for the Nation (<https://waterdata.usgs.gov/>), continuous data are available at 15-minute increments for a variety of metrics, including discharge, gage height, and water turbidity. A glimpse of the raw data for gage height appears in **Table 1**.

Table 1: USGS Continuous Gage Height Raw Data

agency_cd	site_no	datetime	tz_cd	gage_height_ft
USGS	12045500	2008-01-01 00:00	PST	11.21
USGS	12045500	2008-01-01 00:15	PST	11.21
USGS	12045500	2008-01-01 00:30	PST	11.20
USGS	12045500	2008-01-01 00:45	PST	11.19
USGS	12045500	2008-01-01 01:00	PST	11.18

II.B. Sediment Data

Data on sediment load and suspended sediment concentration were obtained from the USGS ScienceBase repository (<https://doi.org/10.5066/F7PG1QWC>) published in support of the 2018 article by Ritchie, et al. titled “Morphodynamic evolution following sediment release from the world’s largest dam removal” (see **Appendix**). These data were measured and estimated at USGS gaging station #12046260, located on the Elwha River downstream from the Elwha Dam site. Daily data were reported from September 15, 2011 (the start of the Elwha Dam removal) through September 30, 2016 (2 years following the completion of the Glines Canyon Dam removal).

The raw daily sediment data contained 1843 observations and 18 variables measuring daily discharge, sediment concentration, sedimend load and bedload, and sediment discharge. Over this 5 year period, daily suspended sediment concentration data is missing for 10 days. In our analysis, we interpolated these missing data points using linear interpolation. **Table 2** shows a glimpse of the raw data for the daily suspended sediment concentration and load variables, which are of interest for our analysis.

Table 2: Daily Sediment Concentration and Load Raw Data

day	daily_ssc_mg_l	daily_suspended_sediment_load_tonnes
08/26/2015	0.4568460	0.3
08/27/2015	0.4472032	0.2
08/25/2015	0.4394357	0.2
08/24/2015	0.5156313	0.3
08/23/2015	0.5078074	0.3

II.C. Water Quality Data

Water quality data were obtained from USGS ScienceBase repository (<https://doi.org/10.5066/F75B00N4>) published in support of the 2020 article “Ecological parameters in the Elwha River estuary before and during dam removal” by Foley et al (see **Appendix**). Water quality was measured at two sites before removal (2006-2007) and five sites during/after removal (2013-2014). Concentration and physical characteristic measurements include phosphate, nitrate and nitrile, ammonium, salinity, temperature, turbidity, dissolved oxygen, percent dissolved oxygen, and pH. Turbidity measurements from this dataset were not utilized because sediment analysis is being conducted elsewhere. **Table 3** shows a glimpse of the raw water quality data, though the columns are truncated. In the complete dataset, a column is assigned to each water quality parameter and longitude and latitude are given.

Table 3: Daily Sediment Concentration and Load Raw Data

Dam.Condition	Date.Collected	Site.Name	Phosphate.concentration
Before removal	6/22/06	ES1	0.03
Before removal	6/22/06	ES2	0.09
Before removal	7/20/06	ES1	0.04
Before removal	7/20/06	ES2	0.08
Before removal	8/31/06	ES1	0.09

II.D. Salmon Diet Data

Data concerning the dietary intake of two salmon species, Chinook and Coho, was obtained from USGS ScienceBase repository (<https://doi.org/10.5066/F75B00N4>), published in support of “Ecological parameters in the Elwha River estuary before and during dam removal” by Foley et al (see **Appendix**). In this dataset, the composition of Chinook and Coho salmon diets are made available from stomach content analysis. Fish were collected for sampling throughout 2006-2007 (“Before”) and 2013-2014 (“During”). It is important to note that although 2013 and 2014 are considered “During” dam removal, it is important to note that the Elwha Dam, which is lower on the river, was completely removed by 2012. This means that salmon were able to travel up the river more than had been possible for the last 100 years.

For Chinook, 93 and 164 fish were sampled from before and during removal, respectively. For Coho, 23 and 112 fish were sampled from before and during removal, respectively. 193 unique taxa were screened for. **Table 4** shows a glimpse of the dataset, with the columns being truncated for clarity. In the complete dataset, each taxa screened for is assigned a unique column.

Table 4: Daily Sediment Concentration and Load Raw Data

Date	Dam.condition	Year	Season	Fish	Sampling.event	Replicate	Acari...larva
5/11/06	Before	2006	Spring	Chinook		1 9	0
5/11/06	Before	2006	Spring	Chinook		1 10	0
5/11/06	Before	2006	Spring	Chinook		1 20	0
5/11/06	Before	2006	Spring	Chinook		1 21	0
5/11/06	Before	2006	Spring	Chinook		1 22	0

III. Exploratory Analysis

III.A. Streamflow

We focused on river discharge and gage height data to analyze changes to river hydrology following dam removal. **Table 2** outlines the availability of river discharge and gage height data at each USGS monitoring site along the Elwha River.

Table 5: Availability of USGS Streamflow Data

Site No.	Relative Location	Dates Available	
		Discharge	Gage Height
12044900	Above Glines Canyon Dam	Mar 1994–Sept 2011	Oct 2007–Nov 2015
12045500	Between Glines Canyon and Elwha Dams	Oct 1989–Present	Oct 2007–Present
12046260	Below Elwha Dam	Unavailable	Unavailable

Our goal is to analyze Elwha River streamflow before, during, and after the dam removal, which occurred over the period 2011–2014. Therefore, based on data availability, we downloaded discharge data from USGS site #12045500 and gage height data from USGS sites #12044900 and #12045500. We pulled continuous data over the period 2008–2017 (as available) to capture a 10-year window surrounding the dam removal.

We plotted the time series data to get a sense of how discharge and gage height trend over time. **Figures 4 and 5** show daily average discharge (in cubic feet per second) and gage height (in feet), respectively, measured at the USGS monitoring sites with available data over 2008–2017. Daily averages were calculated over all 15-minute increments recorded each day. Over this 10-year period, discharge data were missing for 130 days. For our analysis, we interpolated discharge on these days using linear interpolation.

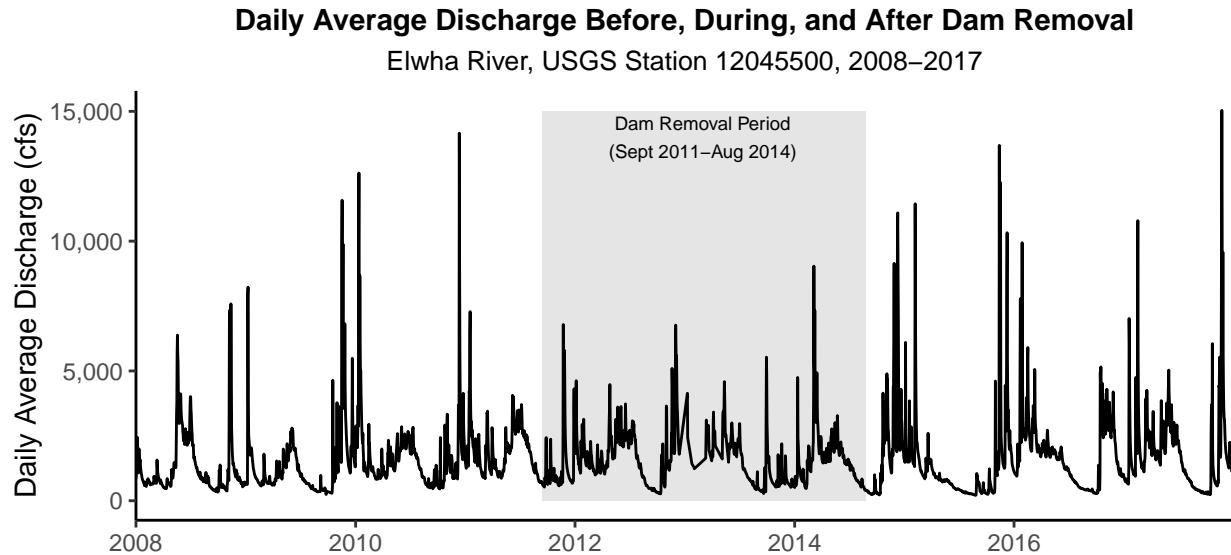


Figure 4: Elwha River Daily Average Discharge at USGS Site 12045500 (2008–2017)

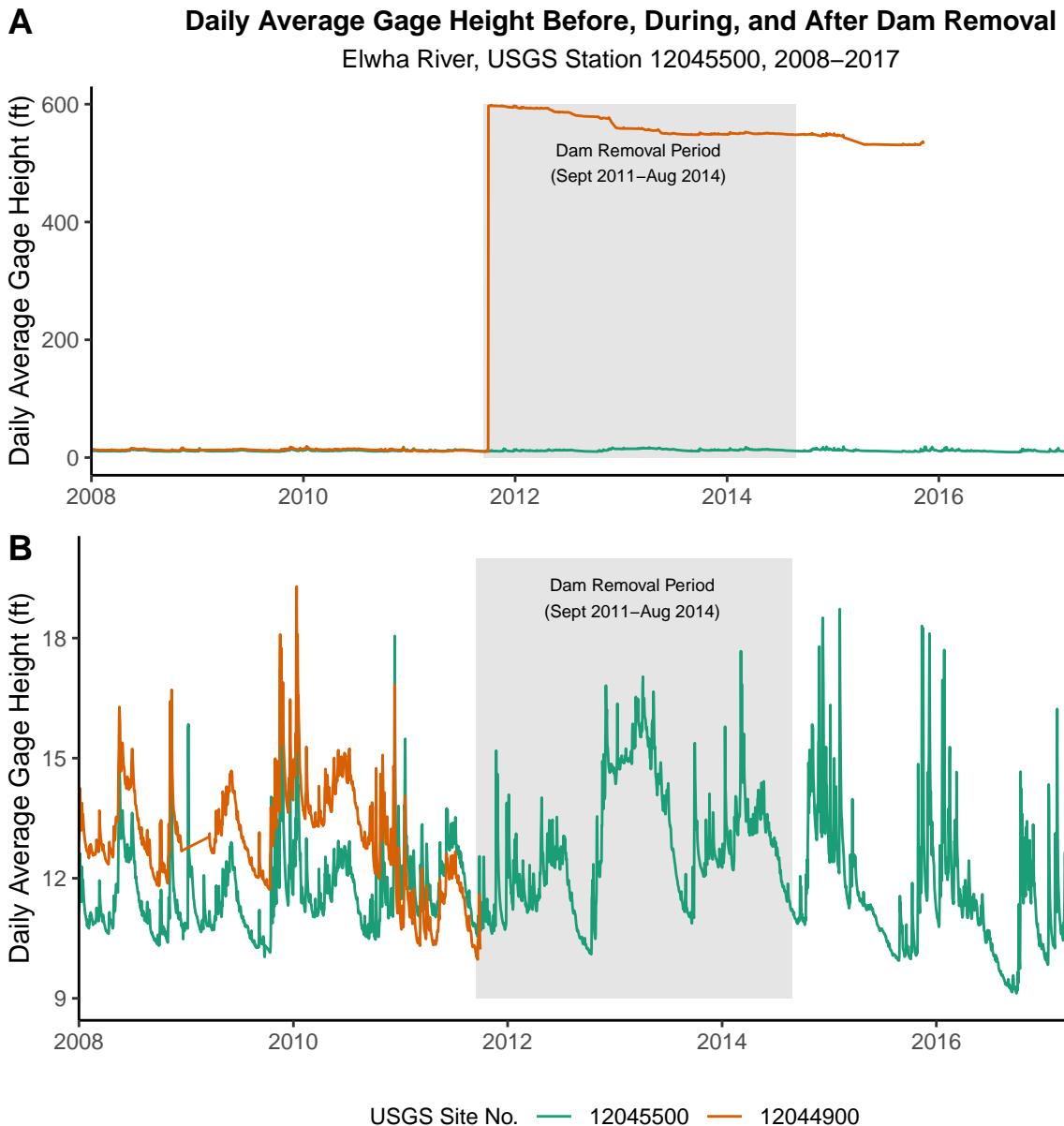


Figure 5: Elwha River Daily Average Gage Height (2008–2017)

As is apparent in **Figure 5.A**, gage height at USGS Site #12044900 (located upriver from the Elwha Dam) spiked immediately from 10 ft to nearly 600 ft at the start of the Elwha Dam removal in September 2011. We hypothesize that this spike is due to a change in the zero level used to measure relative stream stage. Because the cause and characterization of this spike is unknown, we chose to exclude observations from this location and focus only on USGS Site #12045500 for our analysis of gage height. A time series analysis of the streamflow data collected at this monitoring site is discussed further in **Section IV.A** below.

III.B. Sediment

Over the dams' 100-year lifetime, nearly 30 million tonnes of sediment had been trapped behind the Elwha and Glines Canyon dams (Coastal Watershed Institute, 2022). Removal of the dams along the Elwha River released over 10 million tonnes of sediment trapped in the dams' reservoirs (East et al., 2015). Our goal is to use suspended sediment concentration and load data measured downstream of both dams (USGS Site #12046260) to understand how dam removal changed the river's sediment budget, therefore impacting river morphology.

Figure 6.A shows the distribution of daily suspended sediment concentrations observed during and after dam removal, with values ranging from 0.22 to 13,819 mg/L. **Figure 6.B** shows the distribution of daily sediment load, with values ranging from 0.1 to 429,807 tonnes.

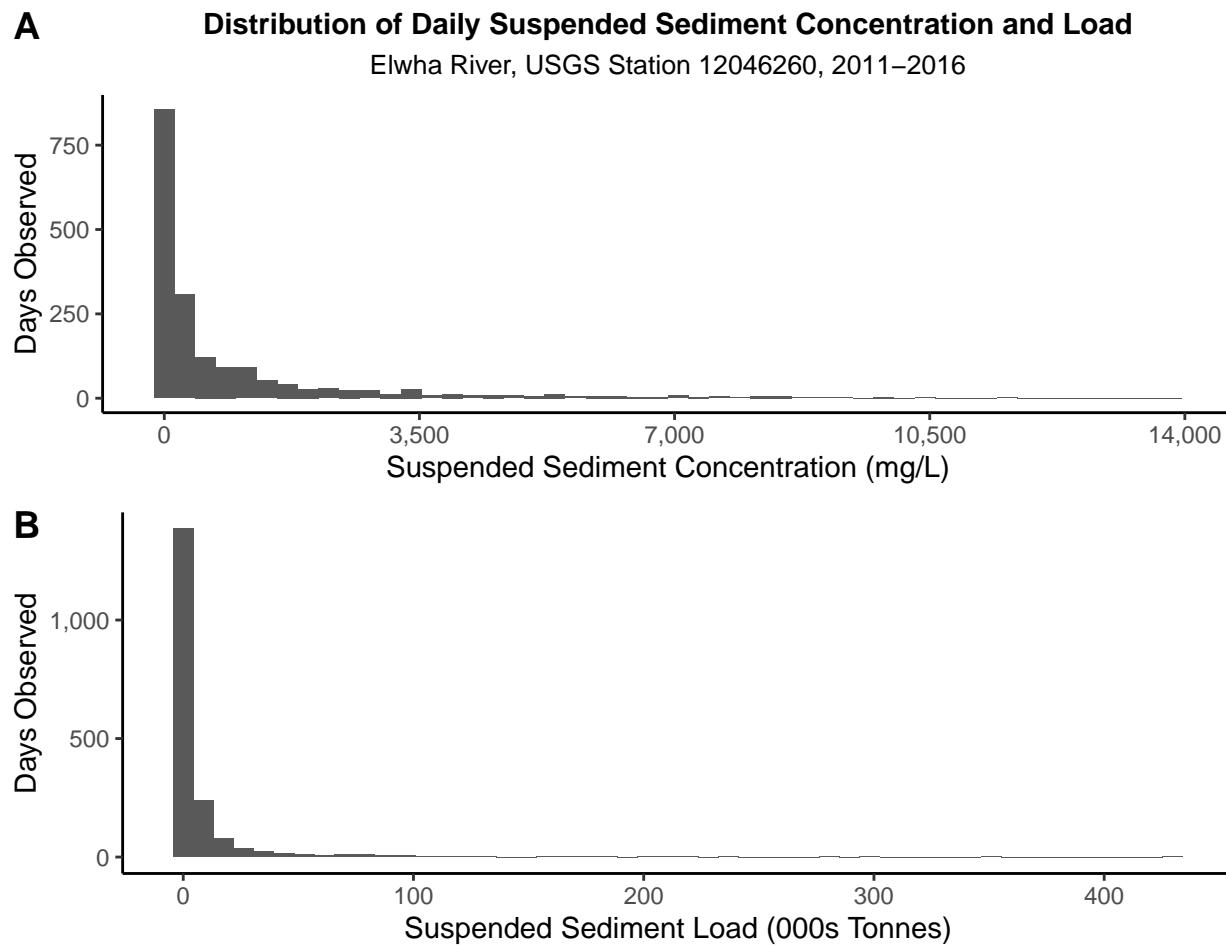


Figure 6: Distribution of Daily Suspended Sediment Concentration and Load at USGS Site 12046260 (2011–2016)

Figure 7 shows suspended sediment concentration and load measured downstream both dams over the five-year period during and after dam removal. Because of the wide range of observed concentrations, the data are grouped into buckets to better visualize a trend in sediment concentration over time. Each bar in **Figure 7.B** represents a week during the five-year period and is colored according to the suspended sediment concentrations recorded throughout the week. Sediment concentrations align closely with peaks in sediment load shown in **Figure 7.A**.

Daily Sediment Load and Concentration During and After Dam Removal

Elwha River, USGS Station 12046260, 2011–2016

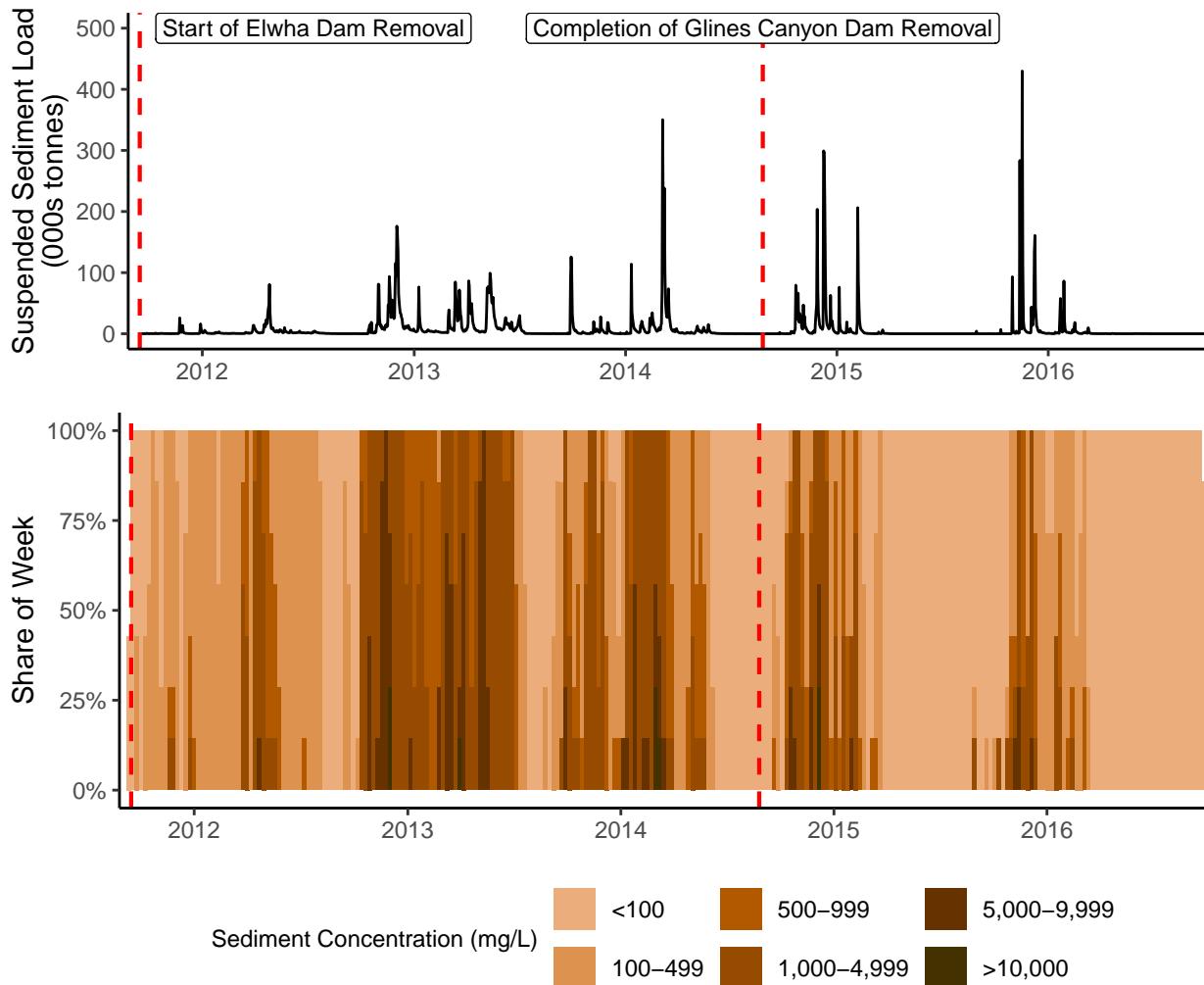


Figure 7: Trends in Daily Sediment Load and Concentration at USGS Site 12046260 (2011–2016)

Figure 7 shows that suspended sediment concentration measured at this point below both dams was sustained at levels greater than 100 mg/L for weeks or months at a time during all three years of the removal period. During both periods during and after removal, suspended sediment load peaks in winter months during winter high flows and snow melt (Ritchie et al., 2018). In **Section IV.B**, we analyze whether suspended sediment load and concentration levels were significantly heightened during dam removal relative to levels after dam removal.

III.C. Water Quality

To better understand the individual trends and suitability of this data for analysis, each parameter was plotted against time. **Figure 8** displays an example of these plots for nitrate concentrations.

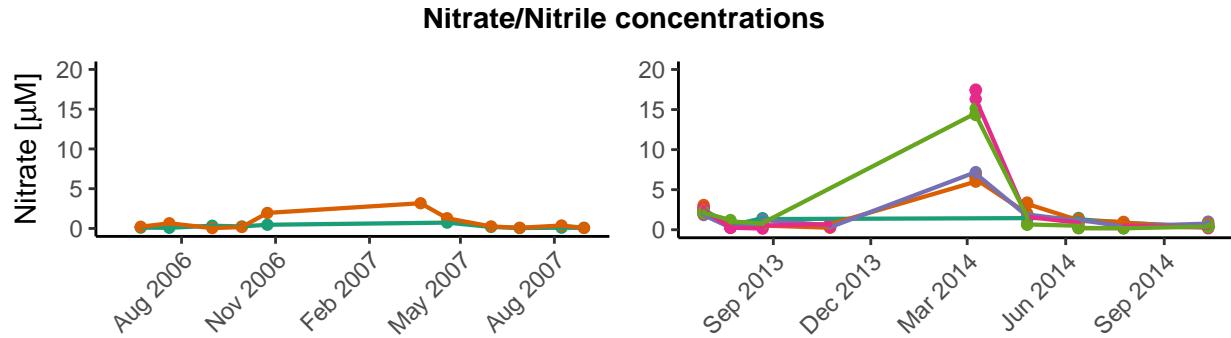


Figure 8: Measured nitrate/nitrile concentration [μM] before and after dam removal

Based on this data exploration, the parameters with useful data are nitrate/nitrile concentration, phosphate concentration, ammonium concentration, and dissolved oxygen. Further analysis of these parameters is included below in **Section IV.C**. The parameters not selected for further analysis are represented here (**Figure 9**). This dataset is limited by the sampling density and locations, specifically by the lack of sampling at all sites across time points.

Water Quality at the Elwha River Estuary Before and During Dam Removal

Dam removal: 2011 – 2014

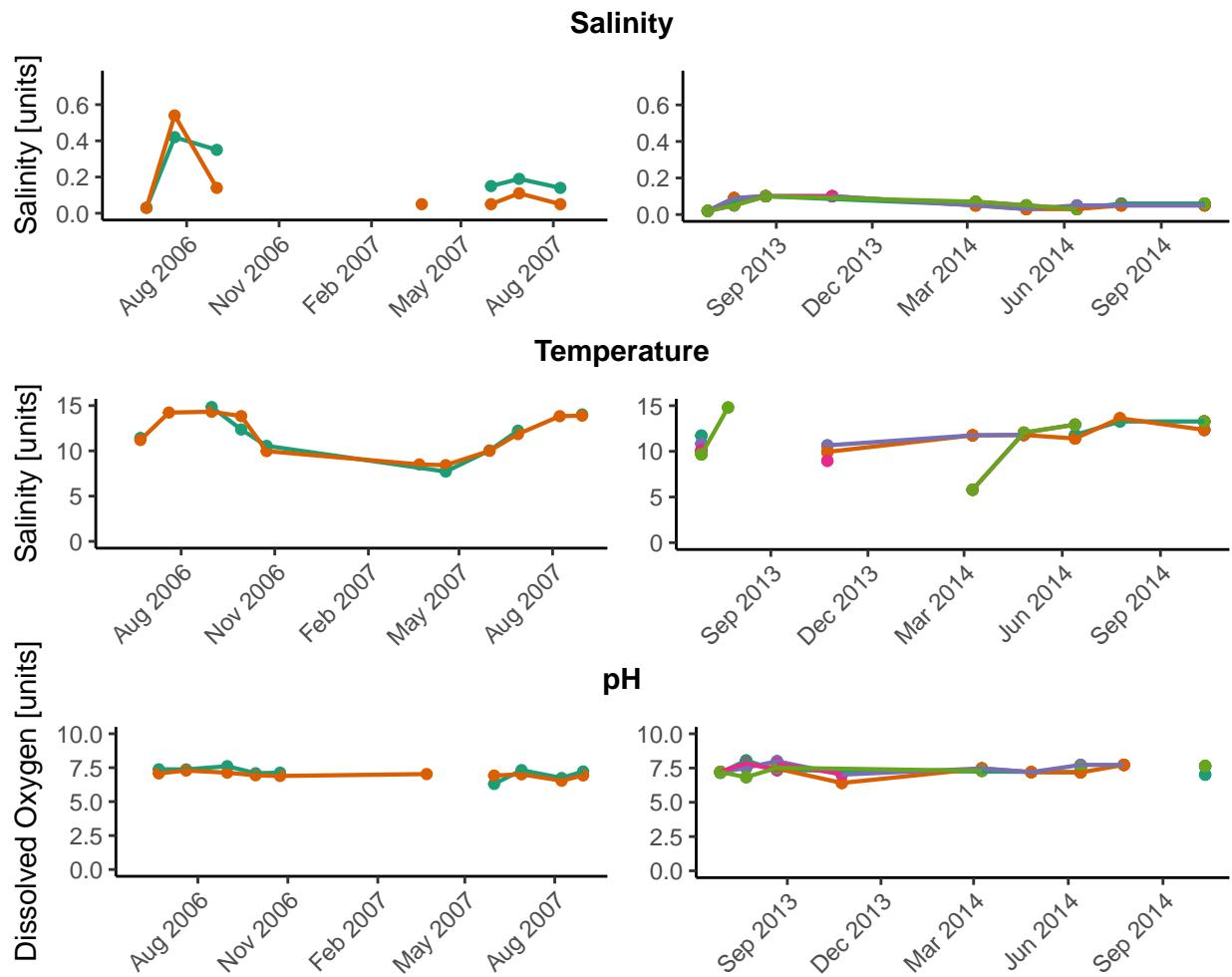


Figure 9: Water quality parameters not selected for further analysis

III.D. Salmon Diet

A dataset that contained the total counts of each taxa count by year, dam condition, and total observations was created. Some taxa are broken into distinct groups, such as Acari, which have entries for both larva and terrestrial (unknown). In the processed dataset, taxa from unique locations or growth stages were combined. In this example, Acari larva and terrestrial (unknown) were summed into a final “Acari” group. **Table 4** shows a glimpse of the Chinook processed dataset, though the counts per year are omitted from this view.

Table 6: Selected rocessed data for Chinook salmon diet

fish	taxa	before_count	after_count	total_count
Chinook	acari	0	0	0
Chinook	acariterrestrial	3	15	18
Chinook	acentrella	1	0	1
Chinook	agabini	0	5	5
Chinook	amphipoda	117	0	117

A limitation of this study is that the number of fish surveyed was not used to normalize the data, so this dataset does not contain relative abundance of consumption across the species as a whole. As the number of times samples were collected greatly increased during the dam removal, this dataset cannot be used to determine the amount of food consumed per fish without further normalization. As such, the goal of this portion of the study is to determine how the dam removal impacted composition of diet, and not abundance of consumption.

IV. Analysis

IV.A. Question 1. How are river discharge and gage height impacted by dam removal?

Figures 4 and 5 above depict daily average discharge and gage height levels recorded at USGS Site #12045500 from 2008 to 2017. We used time series analysis to understand whether a monotonic trend in discharge and gage height along the Elwha River was observed before, during, and after dam removal.

As is evident in Figures 4 and 5.B, both discharge and gage height follow seasonal patterns. We decomposed our time series data to isolate the seasonal component from the overall trend observed over the 10-year period. Figure 10 shows the trend component (in red) overlaying the recorded data for both discharge and gage height. From this figure, it appears that gage height was particularly heightened during dam removal, but there is a less clear trend with regards to discharge.

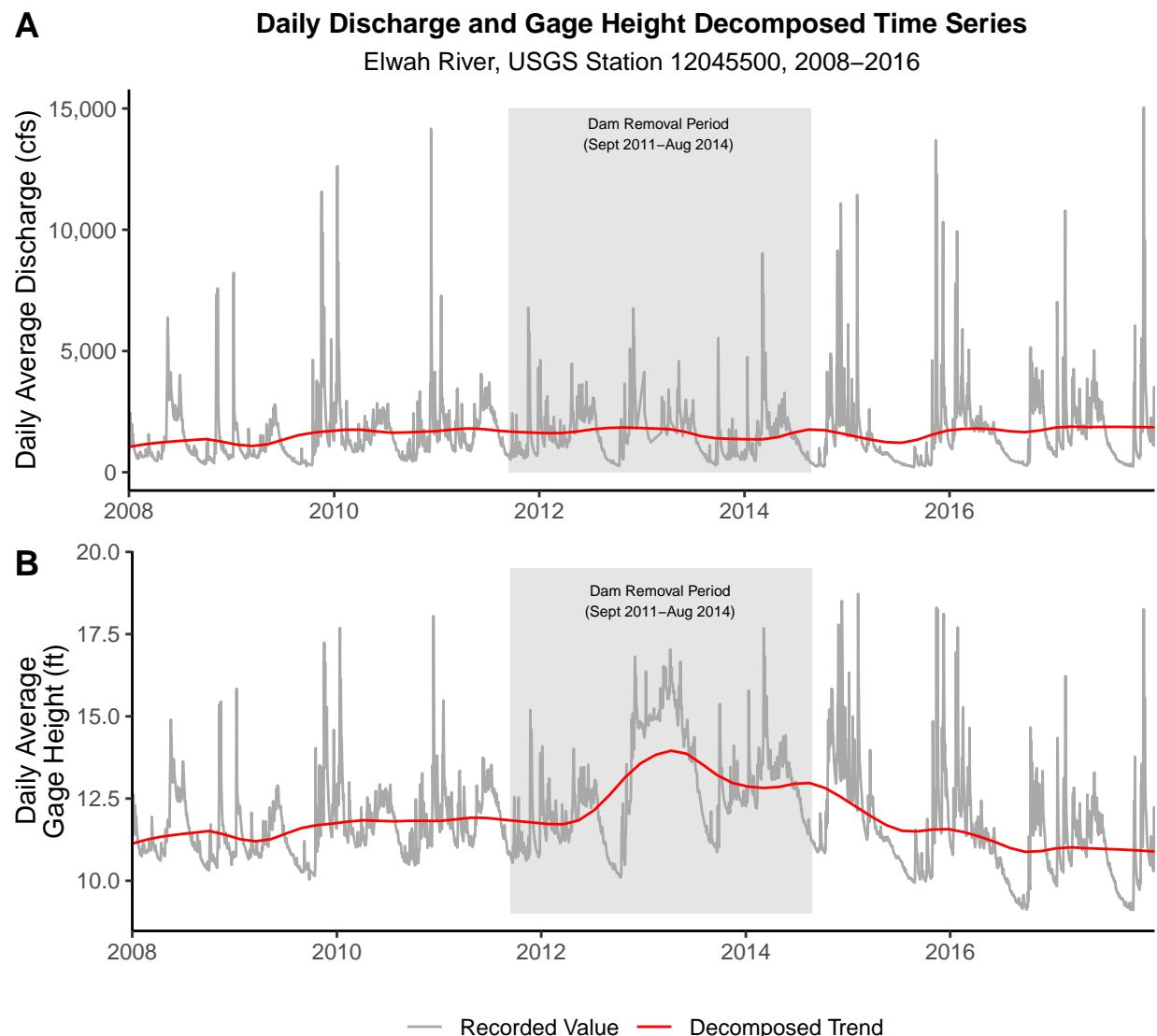


Figure 10: Discharge and Gage Height Decomposed Time Series

For our analysis, we adjusted the discharge and gage height data for seasonality by removing the seasonal component. The seasonally adjusted time series for both datasets were then split into three periods: before the start of removal, during removal, and after removal was completed. A Mann Kendall Test was used to assess whether discharge and gage height were stationary during each period. Results of this analysis are outlined in **Table 7**.

Table 7: Mann Kendall Test of Streamflow Data - USGS Site 12045500

Period	Dates	Discharge (cfs)			Gage Height (ft)				
		Average	Value	P-Value	Tau	Average	Value	P-Value	Tau
Before	Jan 2008–Sept 2011	1,527.67		0*	0.26	11.66		0*	0.24
During	Sept 2011–Aug 2014	1,594.72		8e-04*	-0.07	12.79		0*	0.27
After	Aug 2014–Dec 2017	1,668.79		0*	-0.11	11.41		0*	-0.39

The results of this analysis indicate that there were significant monotonic trends to both discharge and gage height levels over the periods before, during, and after dam removal. From these results, it is difficult to isolate a specific response in streamflow as a result of dam removal. We do observe a particularly strong negative trend ($\tau = -0.39$) in gage height levels after dam removal, which may suggest that river height returned to an equilibrium following the completion of the dam removals.

IV.B. Question 2. Is there a significant impact on sediment load and concentration following dam removal?

As shown in **Figure 7** above and **Figure 11** below, suspended sediment levels appear to be heightened during the period of dam removal compared to levels after removal. We performed a two-sample t-test to assess whether there is a significant difference in mean sediment concentration during and after removal.

The two-sample t-test compared the suspended sediment concentrations recorded during dam removal ($n = 1,077$ days) and after removal ($n = 766$ days). The results from the t-test are presented in **Table 8**. This analysis confirms that suspended sediment concentration was significantly higher in the Elwha River during dam removal relative to after dam removal. While dam removal released millions of tons of sediment trapped behind both dams, suspended sediment concentrations appear to reach an equilibrium several months following the completion of both dam removals.

Table 8: Suspended Sediment Concentration (mg/L) During and After Dam Removal

Period	Dates	Observations	Average (1)
During Removal	Sept 2011–Aug 2014	1077	1,267.68
After Removal	Aug 2014–Sept 2016	766	489.04

Daily Suspended Sediment Concentration During and After Dam Removal
Elwha River, USGS Station 12046260, 2011–2016

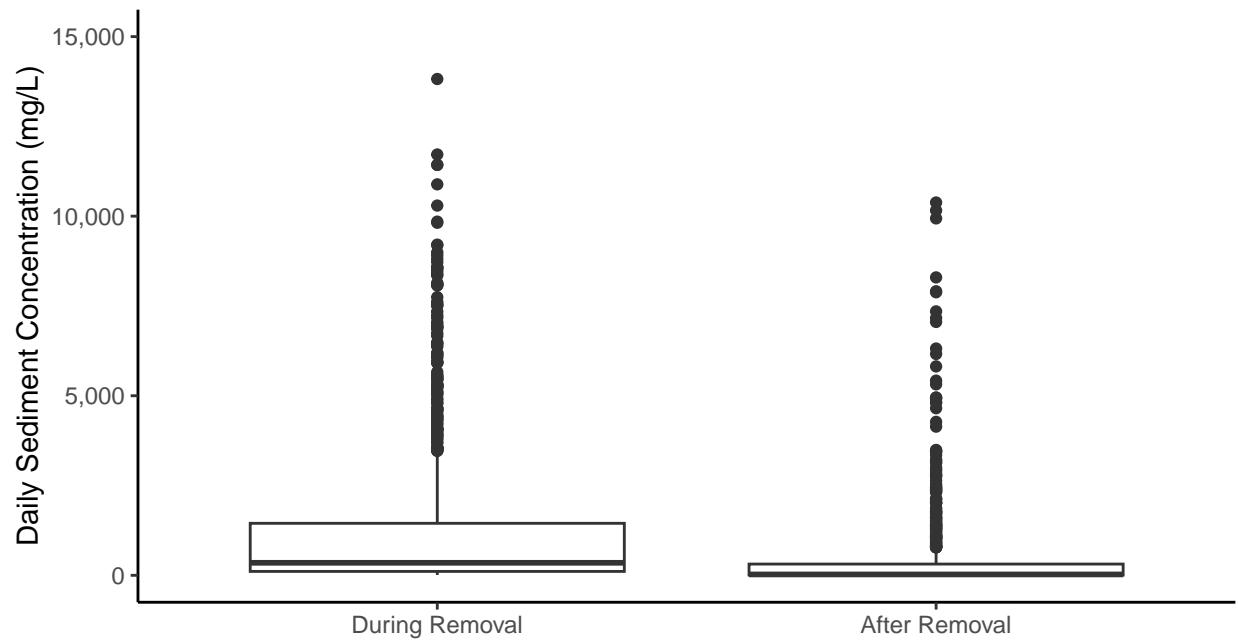


Figure 11: Distribution of Sediment Concentration During and After Dam Removal at USGS Site 12046260 (2011–2016)

IV.C. Question 3. Is water quality and nutrient availability impacted by the dam removal?

Based on the exploratory analysis, only nitrate/nitrile, phosphate, ammonium, and dissolved oxygen concentrations were considered in this water quality analysis (**Figure #**). Each datapoint is based on one reported measurement with no error attached, no statistical analyses were run. Thus, all analysis of this data is based on visual evaluation.

Water Quality at the Elwha River Estuary Before and During Dam Removal

Dam removal: 2011 – 2014

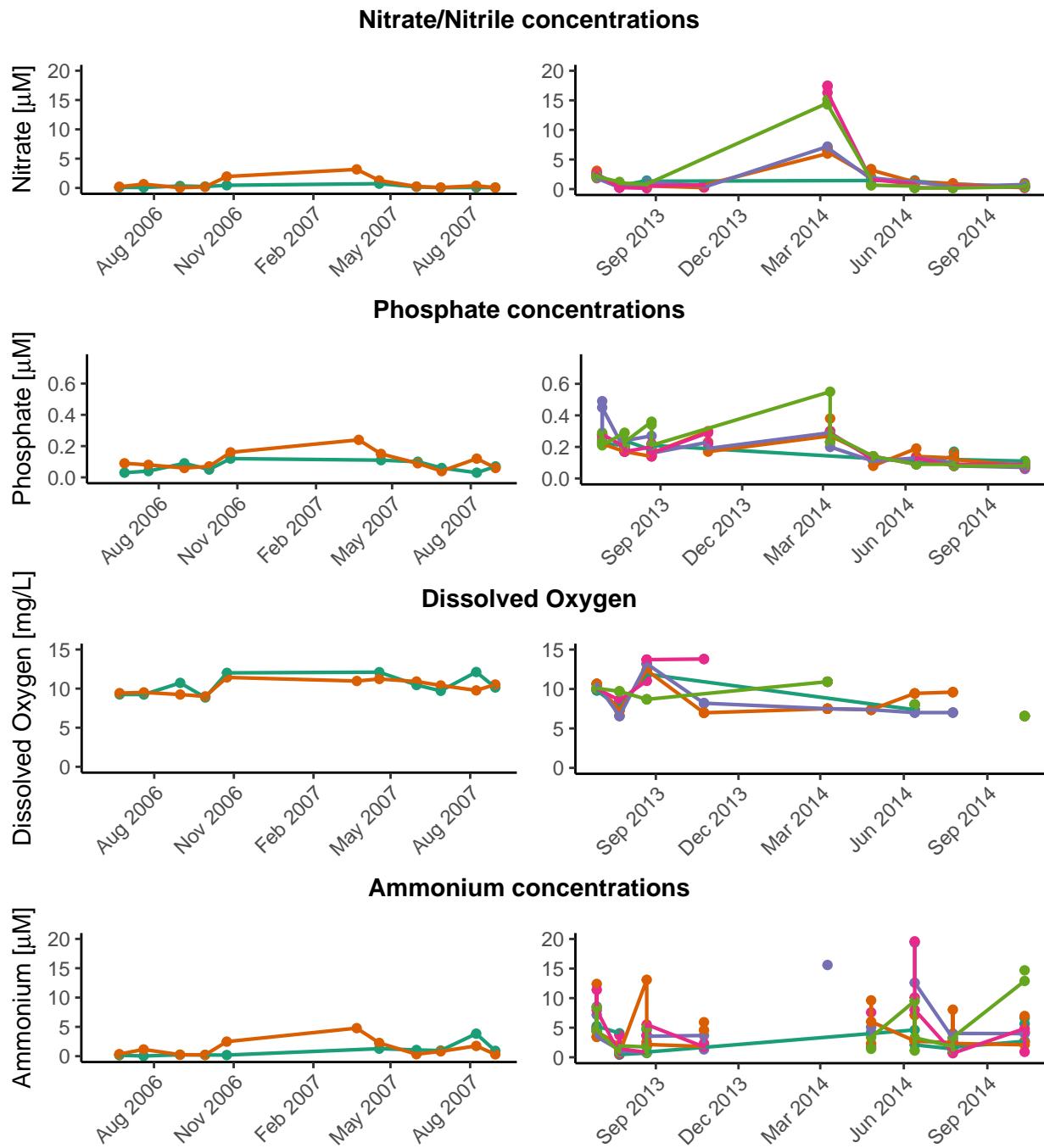


Figure 12: Water quality in the Elwha River estuary before and during dam removal

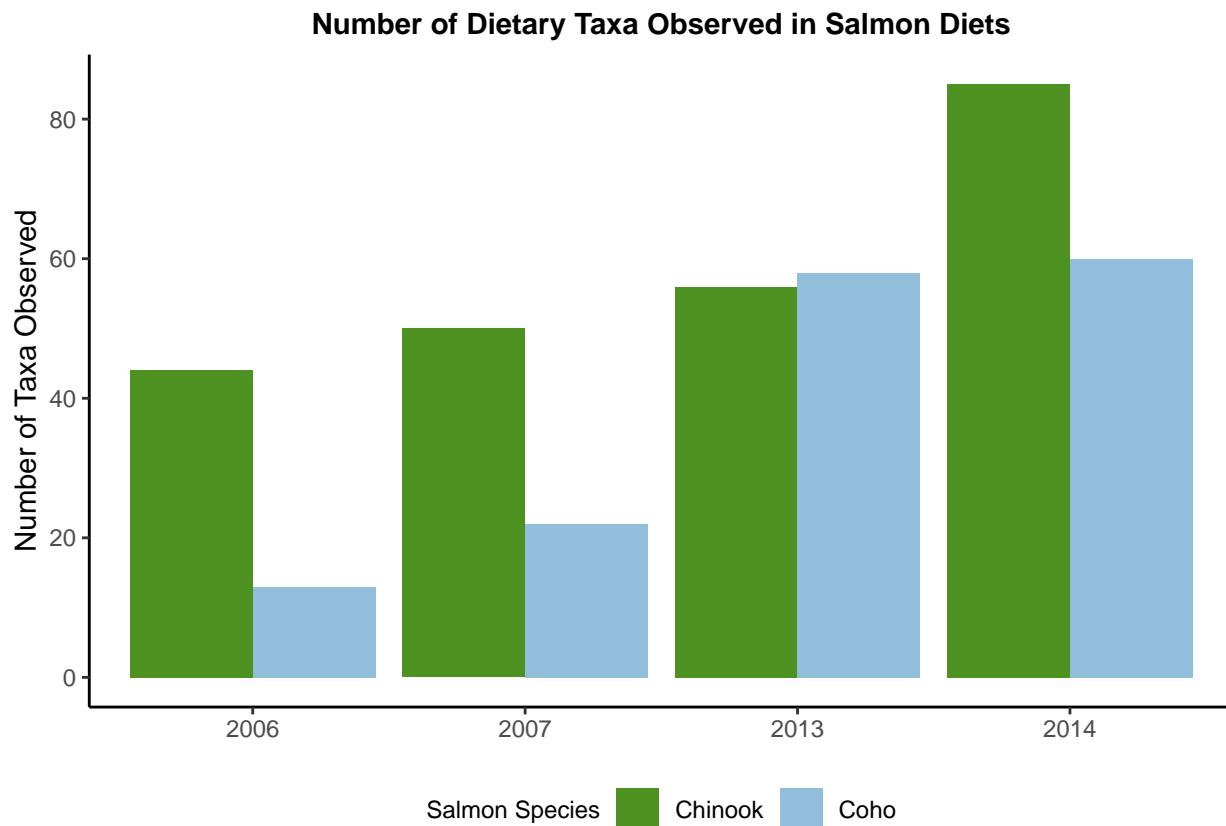
Scientifically, these parameters are all highly interconnected. An increase in nitrates will cause an increase in phosphate, leading to an excess of plant growth and decomposition. As a result, dissolved oxygen will decrease and may impact aquatic animals. Optimal ranges for these compounds include 0.16 - 48.38 uM for nitrate with lower being better (Lehigh University), and 0.05 - 0.53 uM (normal ~ 0.32) for phosphate (University of Wisconsin). Concentrations of all analyzed parameters do not breach unsafe thresholds.

Nitrate/nitrile, phosphate, and ammonium concentrations are consistent or increased during dam removal. At ES2, ammonium concentrations are the most changed between dam conditions. Dissolved oxygen levels appear to decrease during the dam removal at sites that were sampled before and during removal.

Lack of data at all sites before the dam removal makes it difficult to assess if these trends are due to the site specifically or the removal of the dam. The expected relationships described above are generally represented for nitrate, phosphate, and to some extent dissolved oxygen. The data on ammonium are hindered by missing data points in the middle of the time period, but levels do appear to be higher during removal.

IV.D. Question 4. Is there a shift in the types of taxa consumed by salmon before and after the dam removal?

The number of unique taxa consumed by each salmon species was assessed (Figure #).



Before removal and into 2013, the diversity of taxa consumed by Chinook salmon appears largely unchanged. However, there was a large increase in 2014, going from 56 to 85 taxa in 2013 and 2014, respectively. Coho salmon saw more consistency in the diversity of diet in the two dam conditions, where levels were generally similar between the 2006-2007 and 2013-2014. Between 2007 and 2013, an increase in 36 taxa was observed. These results suggest that dam removal had a positive impact on the diversity of both Chinook and Coho salmon diet.

For each year, the top 10 taxa observed were then plotted on a histogram (**Figures # and #**) to assess general trends.

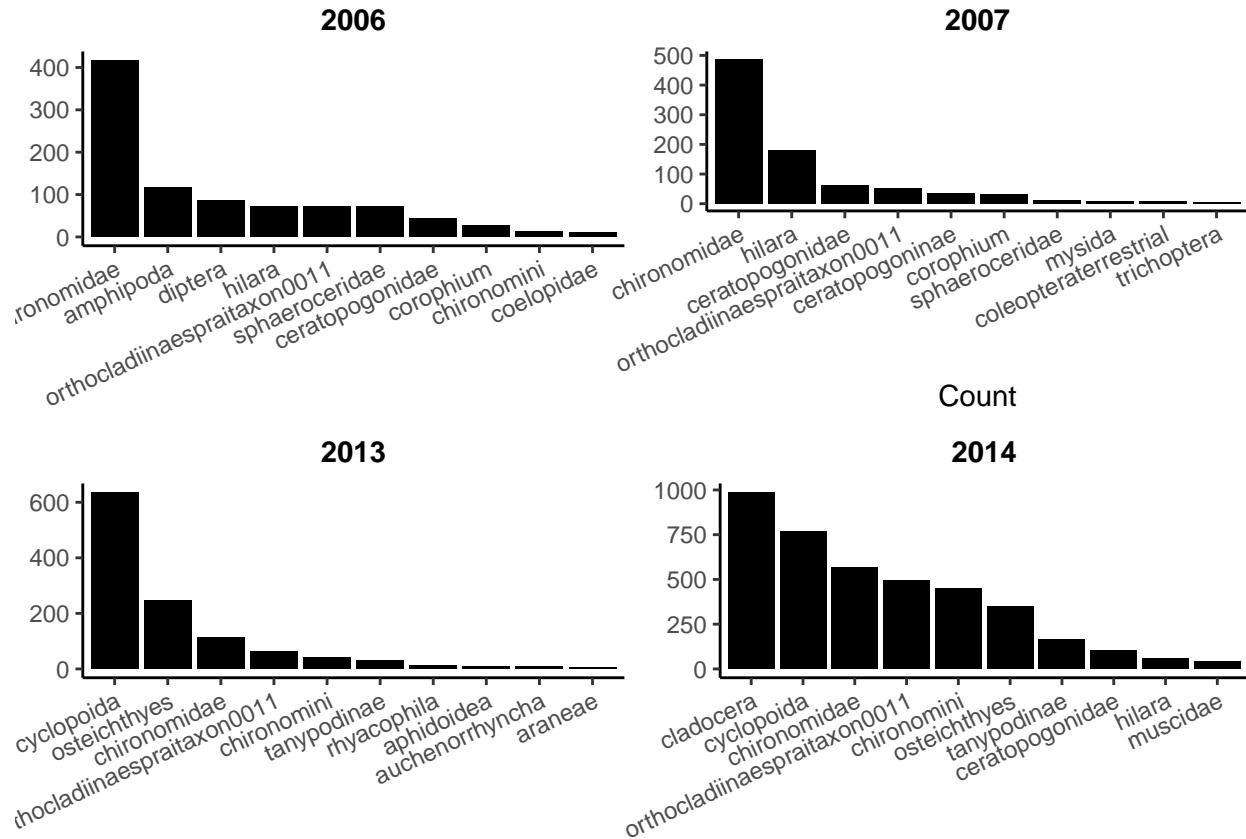


Figure 13: Total counts of the 10 most common dietary taxa each year in Chinook salmon

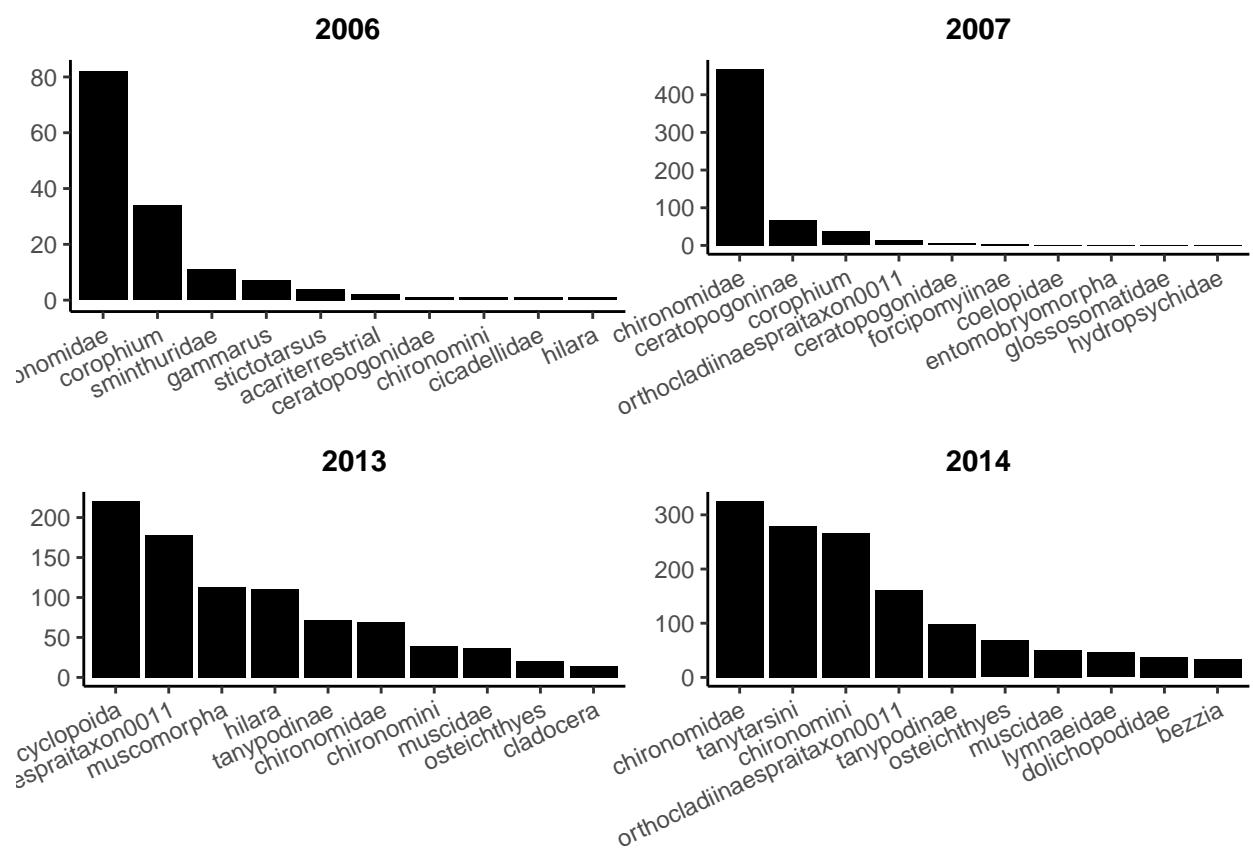


Figure 14: Total counts of the 10 most common dietary taxa each year in Coho salmon

Upon initial investigation, it is clear that the diets of Chinook and Coho salmon have diversified by 2014. Chinook salmon appear more resistant to changes in the diet, as diversification lagged behind Coho by one year. **Need to write more about this later**

To assess how the top taxa were impacted by dam removal, the top ten overall taxa were visualized (the top overall taxa reflect the sum of all counts across all years).

For Chinook salmon, the taxa chironomidae (non-biting midges) are dominant before and after removal (**Figure #**). Other taxa, such as cladocera (water flea), chironomini (within the midge tribe), cyclopoida (order of small crustaceans), and osteichthyes (bony fishes) were present before removal, and either at low counts or not at all after. This could be due to water quality changes that these taxa cannot tolerate or do not prefer, increased choice in foods such that salmon prefer to not eat these taxa, or a number of other reasons. Besides chironomidae, only amphipoda (an order of malacostracan crustaceans) and Hilara (genus of dance flies) saw increased consumption after dam removal as compared to before.

In Coho salmon, chironomidae are the dominant group before and after removal (**Figure # same**). The overall taxa for Coho salmon are certainly dominated by the pre-dam removal state. Few of the taxa identified here have appreciable counts after the removal. This is likely due to the diversification of their diet after removal.

```
## Warning in get_plot_component(plot, "guide-box"): Multiple components found;
## returning the first one. To return all, use 'return_all = TRUE'.
```

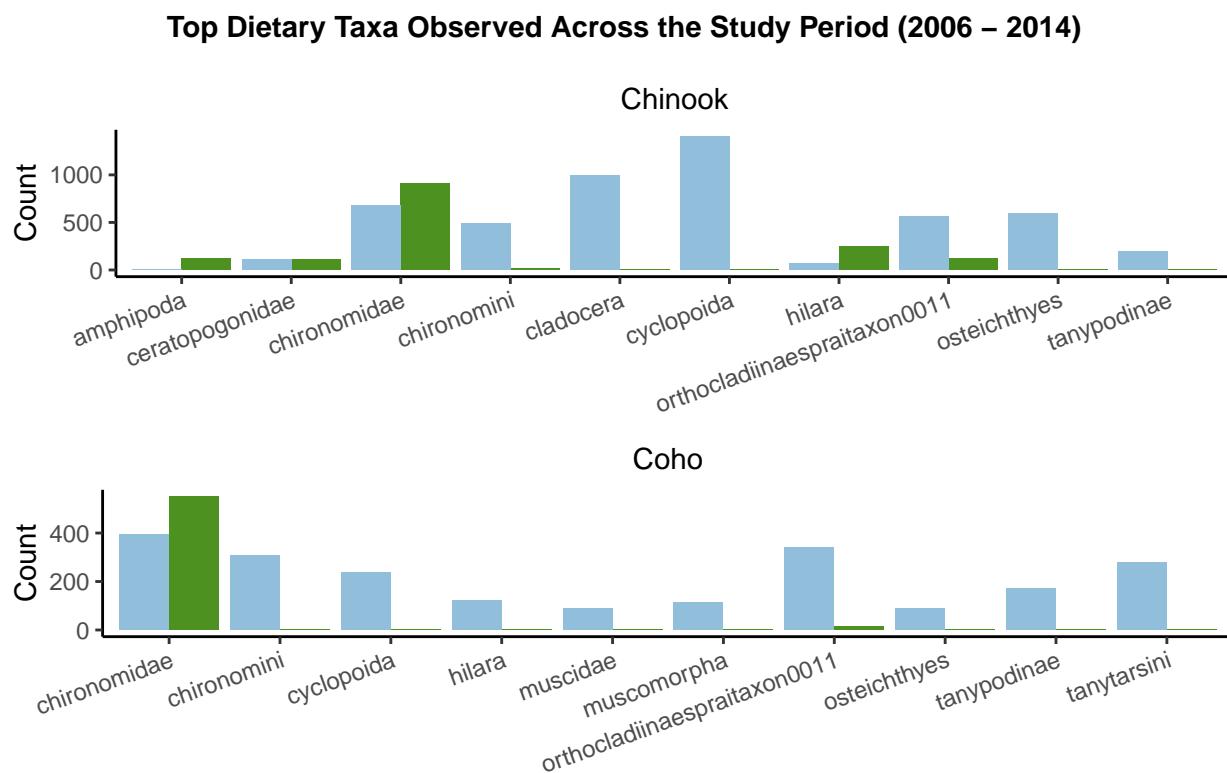


Figure 15: Top taxa for Chinook and Coho salmon before and during dam removal

To better understand the diet of Chinook and Coho during the dam removal, the top taxa observed were plotted (**Figure #**).

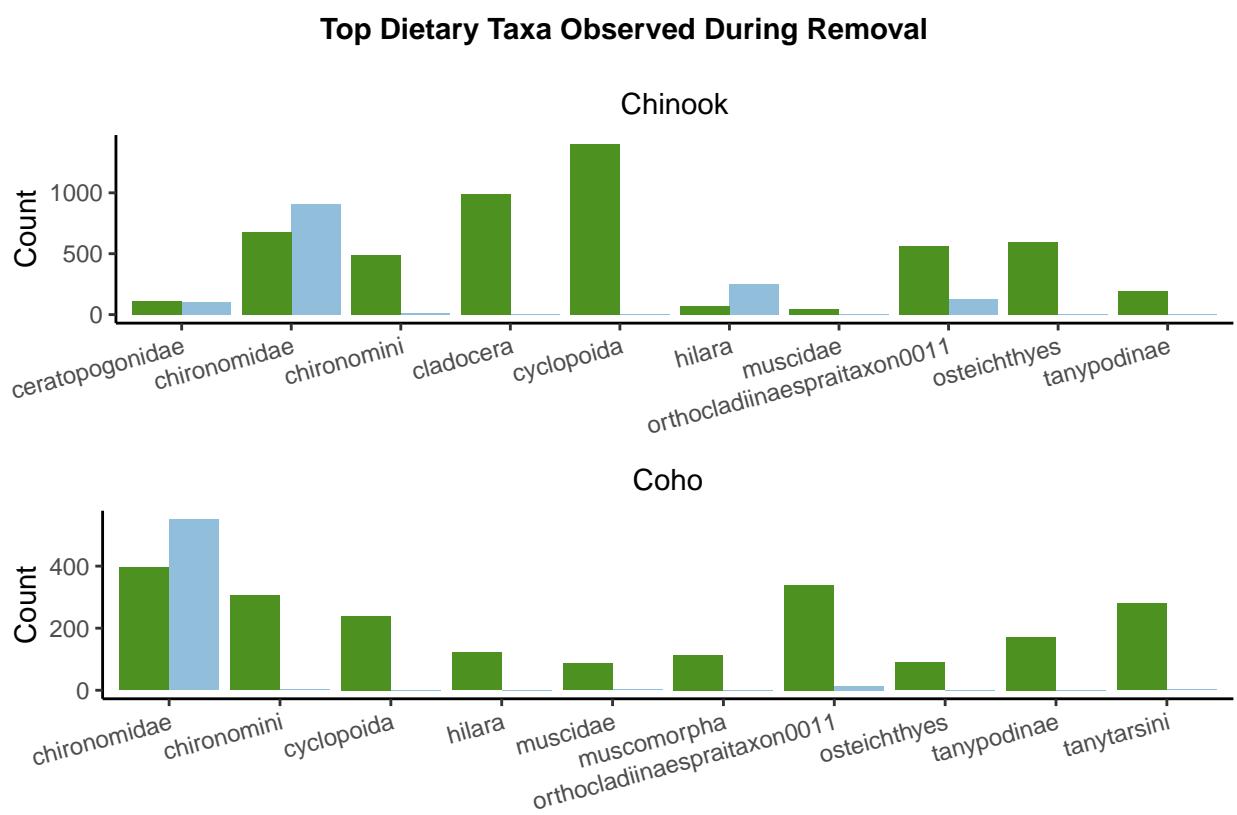


Figure 16: Top taxa for Chinook salmon during dam removal

The taxa consumed by both Chinook and Coho during dam removal is dominated by new species. Between Chinook and Coho, the taxa consumed during the dam removal are similar. Notable overlaps include chironomidae, cyclopoida, and orthocladiinae.

V. Summary and Conclusions

The impact of the removal of two dams from the Elwha River was assessed using physical and ecological endpoints. A number of datasets generated by USGS before, during, and after dam removal were utilized. It is clear that the removal of these dams has had a profound impact on river characteristics and salmon behaviors.

Stream discharge was not greatly impacted over the period analyzed. Discharge levels remained consistent
→ gage height:

from Ritchie et al: “discrete measurements of changes in stage were attributable to 1.0–1.5 m of widespread riverbed aggradation” (means that the deposition of sediment resulted in an increase in riverbed height)

→ sediment River hydrology directly impacts sediment distribution following dam removal. [[examples and cite to East et al. (2015)]]

Water quality was not heavily impacted over the time range analyzed, and levels did not exceed unsafe levels. It does appear that nutrient concentrations were elevated after removal. To fully assess how water quality was impacted by dam removal, significantly more timepoints and locations would have needed to be tested.

The diet of two salmon species, Chinook and Coho, was assessed. Although the data were not able to be normalized, it appears that the diet of both species was diversified by 2014. Chinook salmon appear to be consuming more food than before the dam, but the same is cannot be clearly seen in Coho. Further, the taxa consumed by each species saw some overlap before and after removal, however, new groups were introduced after the dam was removed. Some of the top taxa are shared between the species, such as chironomidae, hilara, and tanypodinae, however, more analysis of these variables would better elucidate the similarities and differences in the diet of Chinook and Coho.

VI. Appendix

VI.A. Data Sources

- Water Data for the Nation, USGS, <https://waterdata.usgs.gov/>
 - USGS Site 12045500: <https://waterdata.usgs.gov/monitoring-location/USGS-12045500/>
 - USGS Site 12044900: <https://waterdata.usgs.gov/monitoring-location/USGS-12044900/>
- Ritchie, A.C., et al., “Daily sediment loads during and after dam removal in the Elwha River, Washington, 2011 to 2016,” 2018, Data in support of 5-year sediment budget and morphodynamic analysis of Elwha River following dam removals: U.S. Geological Survey data release, <https://doi.org/10.5066/F7PG1QWC>.

VI.B. References

<https://geonarrative.usgs.gov/elwhariverrestoration/> <https://projects.seattletimes.com/2016/elwha/>

<https://www.nps.gov/olym/learn/nature/dam-removal.htm>

<https://duke.app.box.com/file/2042213070552>

<https://www.nature.com/articles/s41598-018-30817-8>

— Streamflow

https://waterdata.usgs.gov/blog/gage_height/ <https://www.sciencedirect.com/science/article/pii/S0169555X14004553> <https://coastalwatershedinstitute.org/wp-content/uploads/2022/10/Elwha-Nearshore-Synthesiscwisept2022techmemo-1.pdf>

Foley, M.M., Shafroth, P.B., Beirne, M.M., Paradis, R., Ritchie, A.C., and Duda, J.J., 2020, Ecological parameters in the Elwha River estuary before and during dam removal (ver. 2.0, August 2020): U.S. Geological Survey data release, <https://doi.org/10.5066/F75B00N4>.

— Nutrient concentrations

<https://ei.lehigh.edu/envirosci/watershed/wq/wqbackground/nitratesbg.html#:~:text=in%20a%20watershed?-1,,blood%20cells%20to%20carry%20oxygen.>

chrome-extension://efaidnbmnnibpcajpcglclefindmkaj/https://osse.ssec.wisc.edu/curriculum/earth/Minifact2_Phosphorus.pdf