

# Elwha River Dam Removal

<https://github.com/sylviahipp/KukulaHipp>

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## 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).

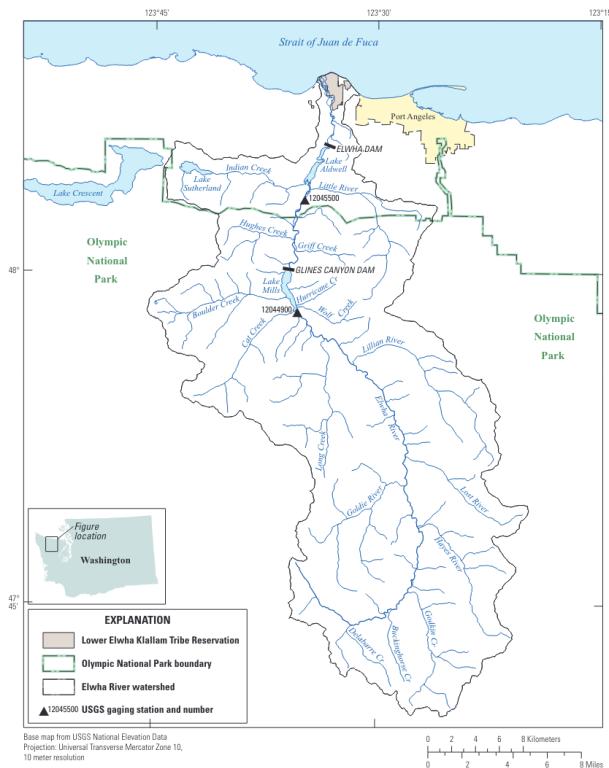


Figure 3: Elwha River watershed, monitoring stations, and dam locations (USGS, 2011)

### 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**. We queried data over a 10-year period before, during, and after dam removal (2008–2017).

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, 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.

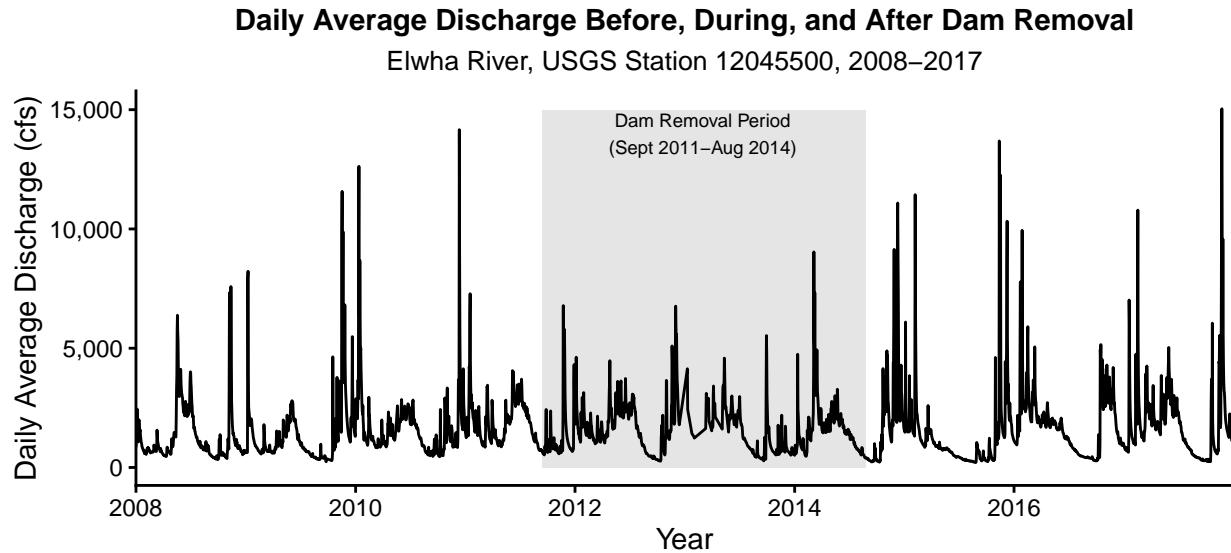


Figure 4: Elwha River Daily Average Discharge at USGS Site 12045500 (2008–2017)

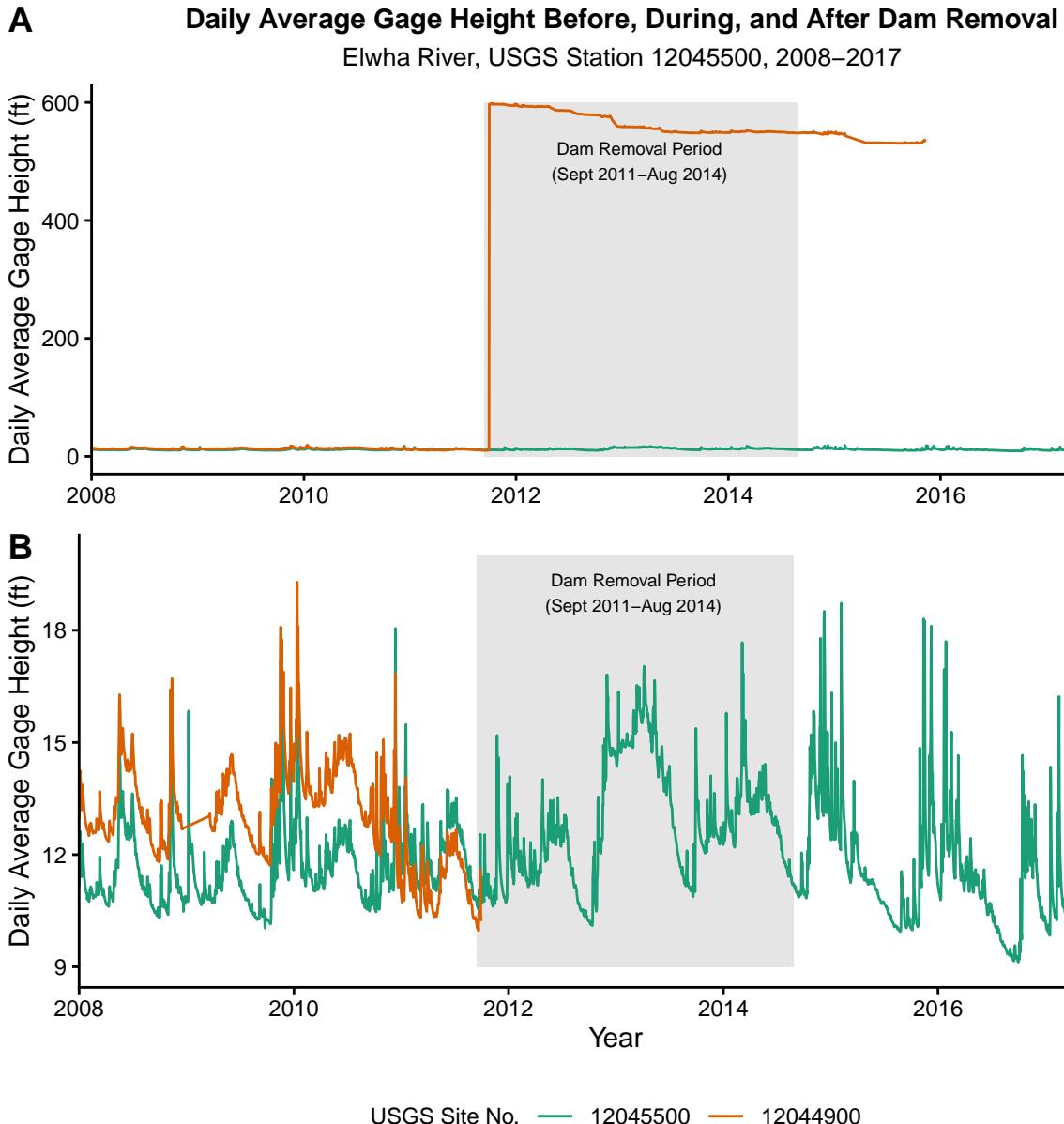


Figure 5: Elwha River Daily Average Gage Height (2008–2017)

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.

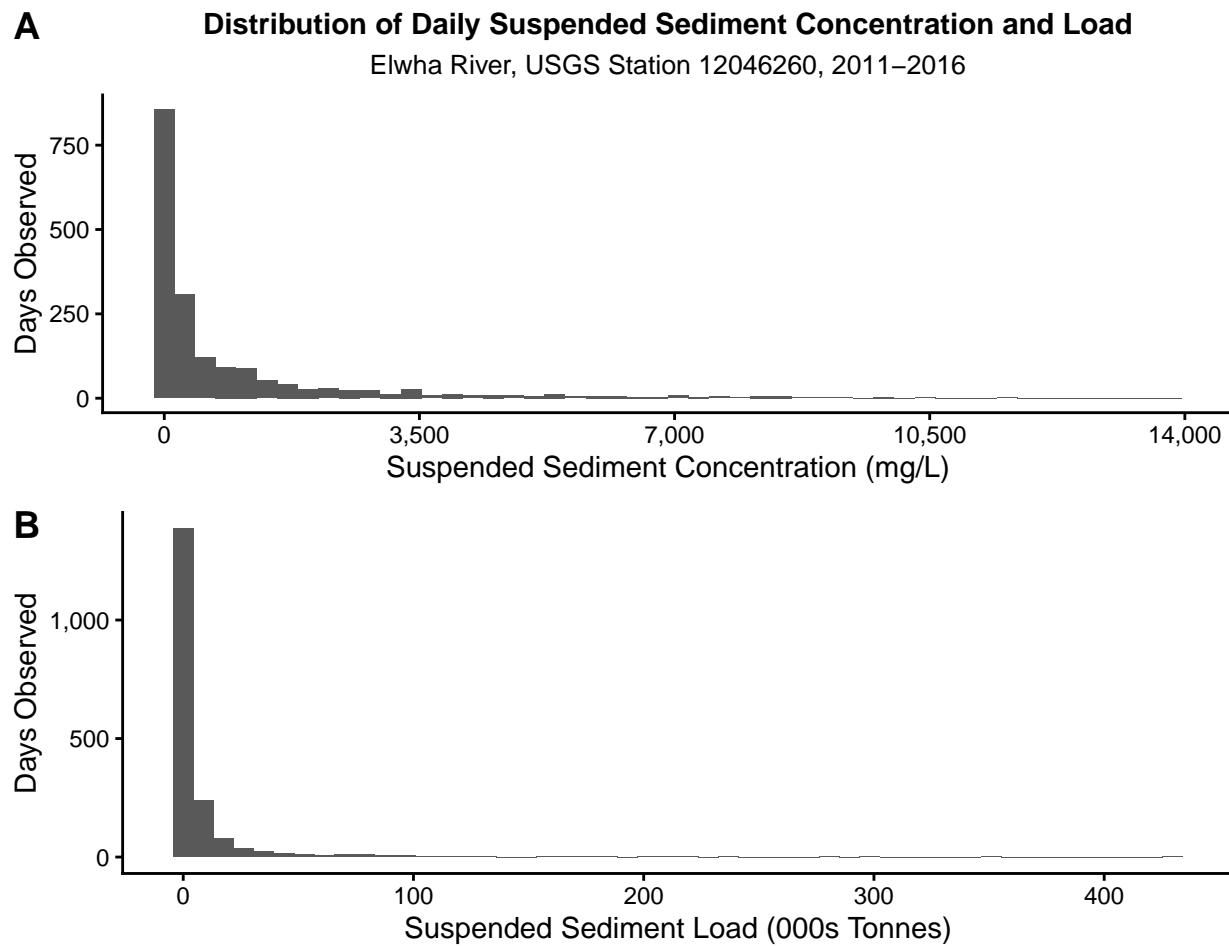


Figure 6: Distribution of Daily Suspended Sediment Concentration and Load at USGS Site 12046260 (2011–2016)

**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

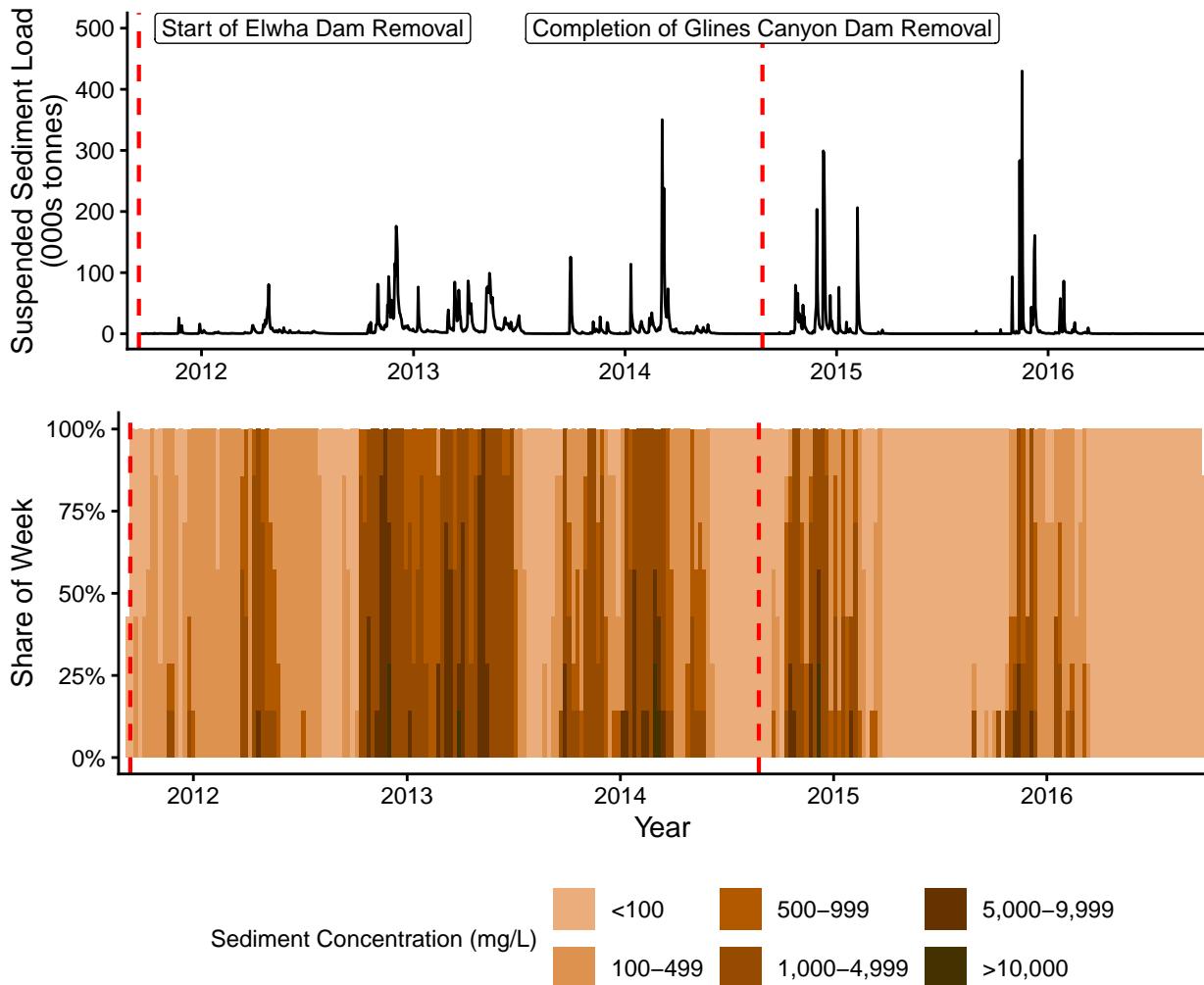


Figure 7: Trends in Daily Sediment Load and Concentration at USGS Site 12046260 (2011–2016)

**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.

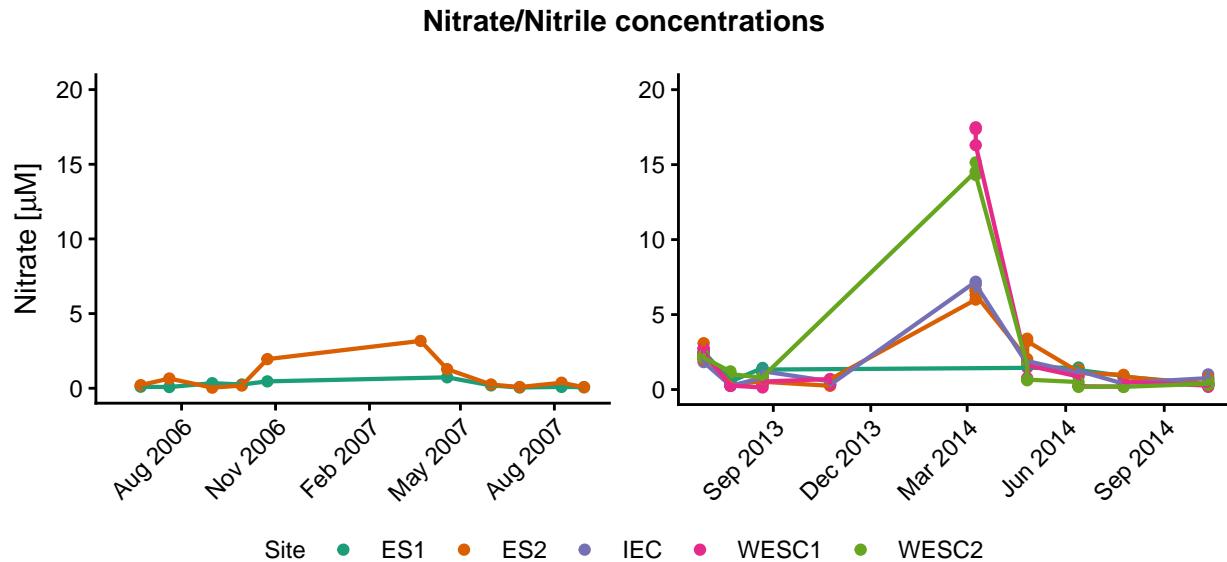


Figure 8: Measured nitrate/nitrile concentration [ $\mu\text{M}$ ] before and after dam removal

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 include salinity, temperature, and pH, and are represented below (**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

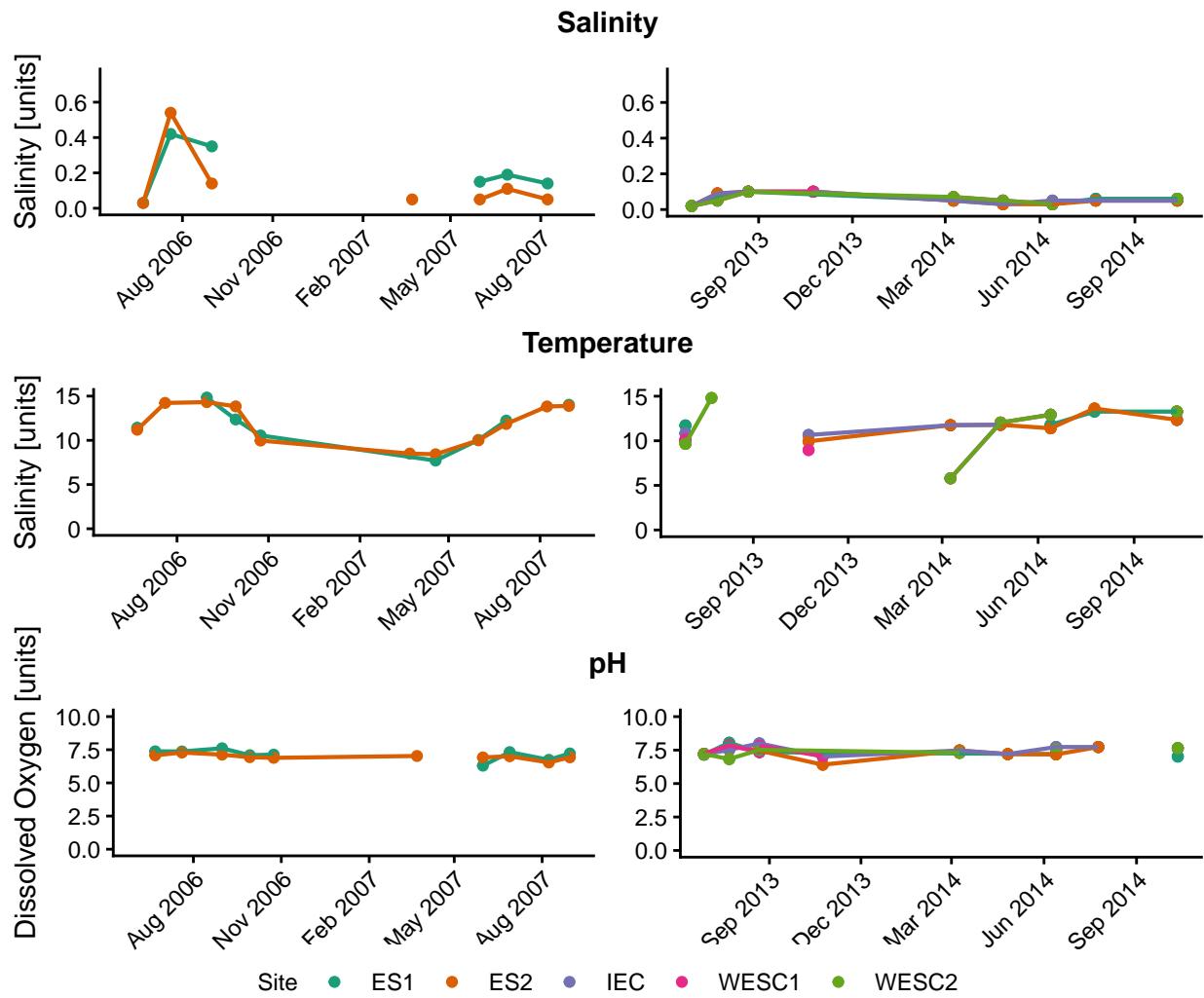


Figure 9: Water quality parameters not selected for further analysis

### 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). **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. **Table 7** summarizes the overall average gage height and discharge levels before, during, and after removal.

Table 7: Summary of Streamflow Data Before, During, and After Dam Removal (2008–2017, USGS Site 12045500)

Period	Dates	Observations	Mean Discharge (cfs)	Mean Gage Height (ft)
Before Removal	Jan 2007–Sept 2011	1,352	1,529	11.7
During Removal	Sept 2011–Aug 2014	950	1,548	12.8
After Removal	Aug 2014–Dec 2017	1221	1,671	11.4

A one-way ANOVA test was used to assess whether discharge and gage height levels were significantly different during each period. **Table 8** summarizes the output of the ANOVA and Post-Hoc analysis. Discharge levels during dam removal were not significantly different from discharge levels before and after removal (p-value of 0.94 and 0.09, respectively). However, discharge levels before removal did differ significantly from discharge levels after removal (p=0.02).

Observed gage height varied much more significantly during removal. Gage height during removal was on-average 1.13 ft and 1.38 ft higher than levels before and after removal, respectively. The ANOVA test confirmed that average gage height levels were significantly different during all periods analyzed.

Table 8: ANOVA Analysis of Streamflow Data Before, During, and After Dam Removal (2008–2017, USGS Site 12045500)

Period	Discharge (cfs)		Gage Height (ft)	
	Difference	P-Value	Difference	P-Value
Before-During	19.63	0.94	1.13	0**
During-After	-122.52	0.09	1.38	0**
Before-After	-142.15	0.02*	0.24	0**

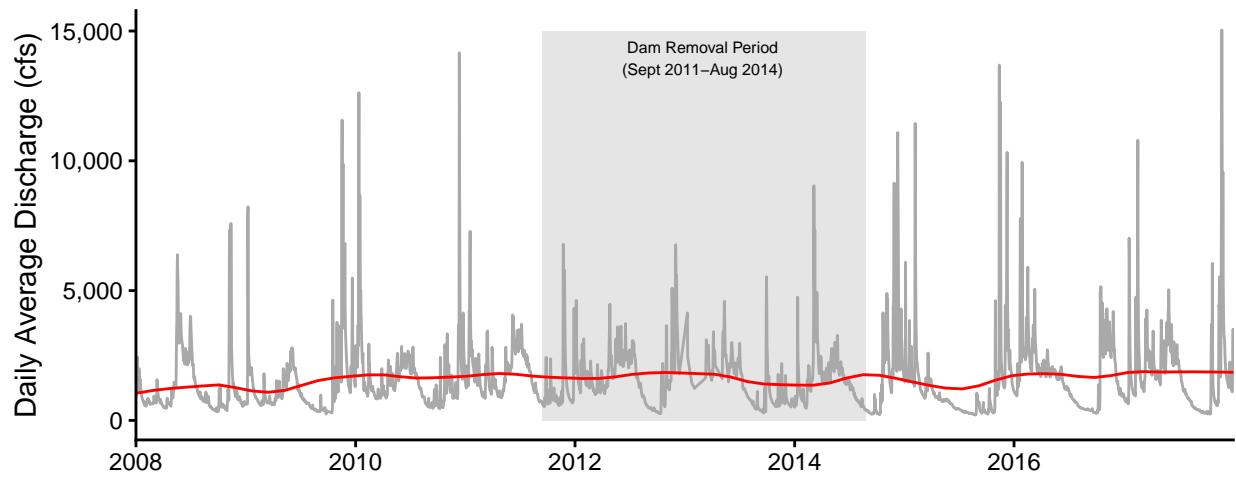
We used time series analysis to understand whether there was a monotonic trend in discharge and gage height along the Elwha River before, during, and after dam removal.

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 increased during dam removal and decreased again following completion. There is a less clear trend with regards to discharge.

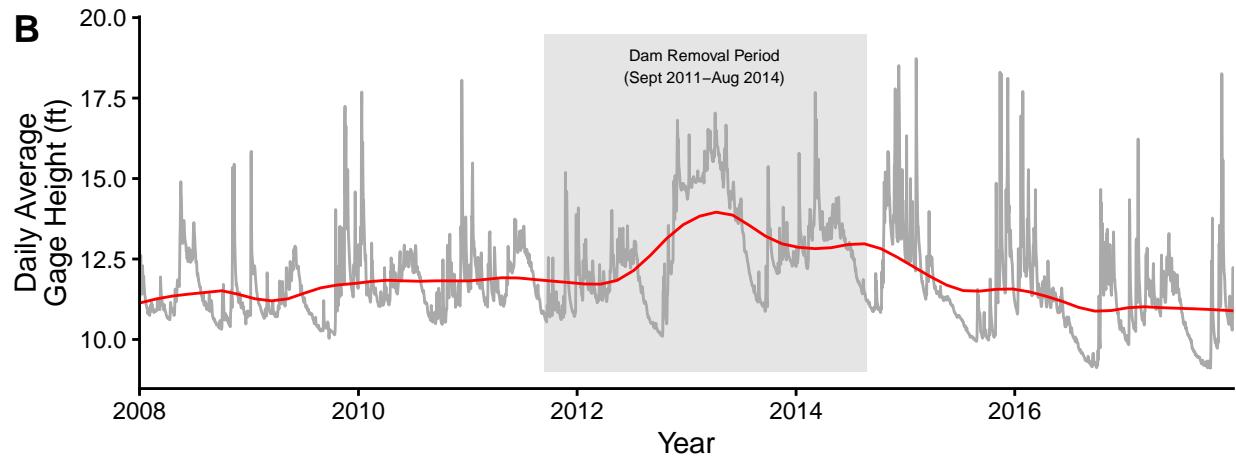
**A**

### Daily Discharge and Gage Height Decomposed Time Series

Elwah River, USGS Station 12045500, 2008–2016



**B**



— Recorded Value — Decomposed Trend

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 9**.

Table 9: 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.

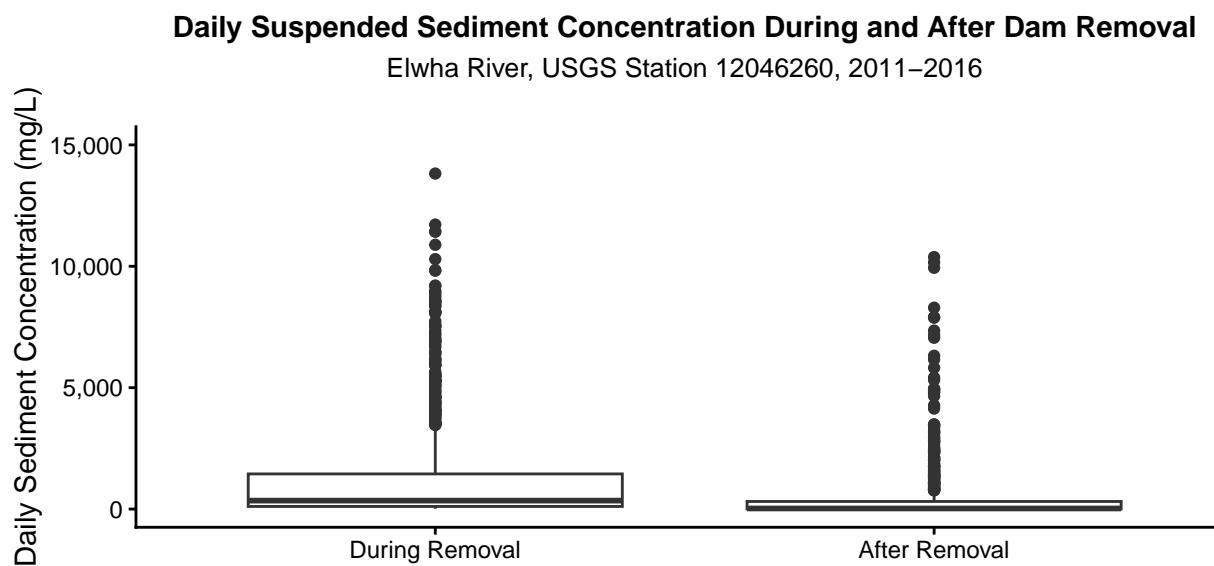


Figure 11: Distribution of Sediment Concentration During and After Dam Removal at USGS Site 12046260 (2011–2016)

A directional two-sample t-test compared the suspended sediment concentrations recording during dam removal ( $n = 1,077$  days) and after removal ( $n = 766$  days). **Table 10** shows a summary of average suspended sediment concentrations before and after removal. This t-test had a p-value of 2.44e-24 (H1 being that levels were higher during removal), which 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 10: Suspended Sediment Concentration (mg/L) During and After Dam Removal (USGS Site 12046260)

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

#### **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 12**). Each datapoint is based on one reported measurement with no error attached, so no statistical analyses were run. Thus, all analysis of this data is based on visual evaluation.

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 around 0.50 uM for phosphate (Lake James Environmental Association).

Nitrate/nitrile, phosphate, and ammonium concentrations are consistent or increased during dam removal, but concentrations do not breach unsafe thresholds. At ES2, ammonium concentrations are the most variable 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.

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

Dam removal: 2011 – 2014

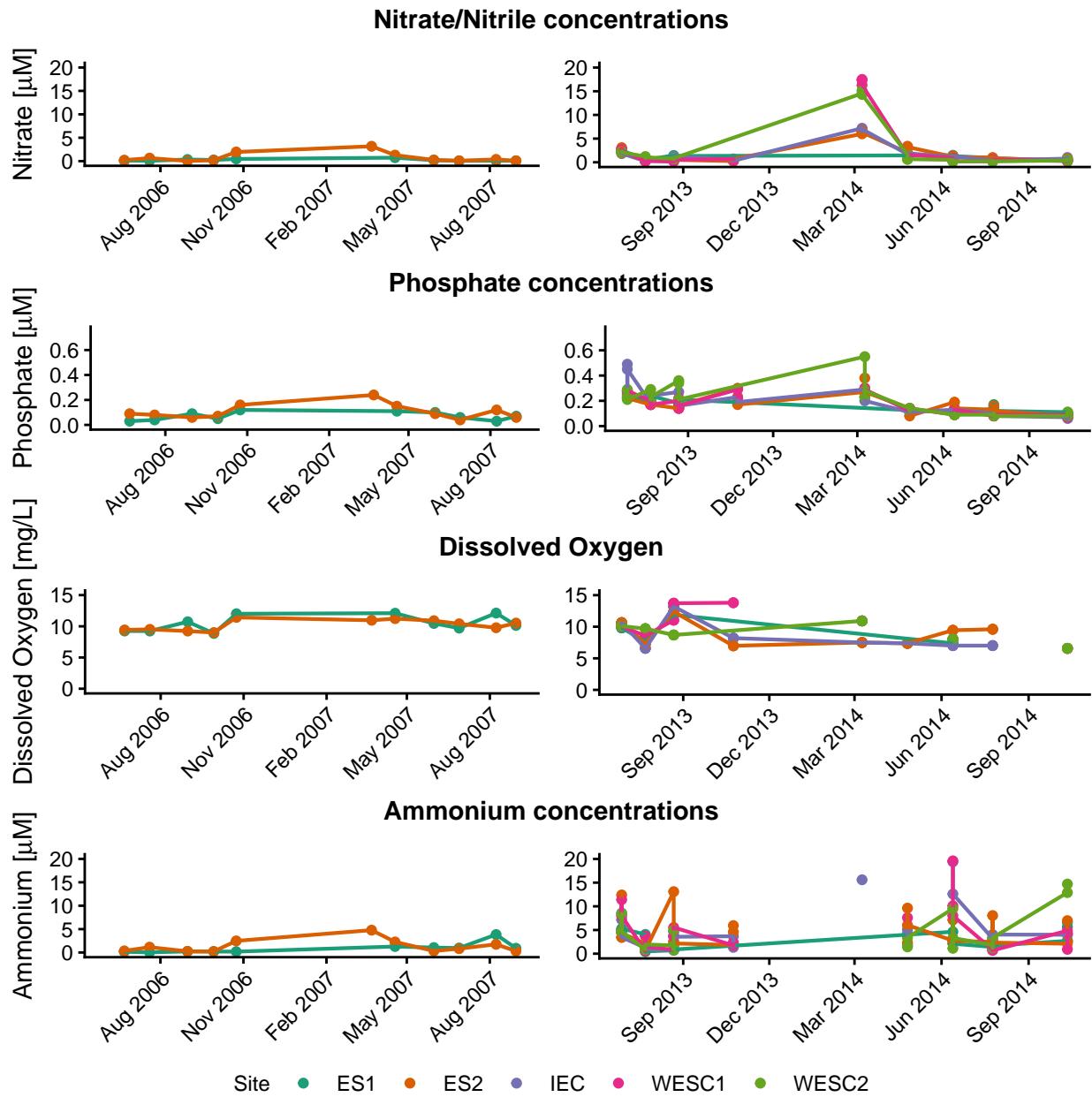


Figure 12: Water quality in the Elwha River estuary before and during dam removal

**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 13**).

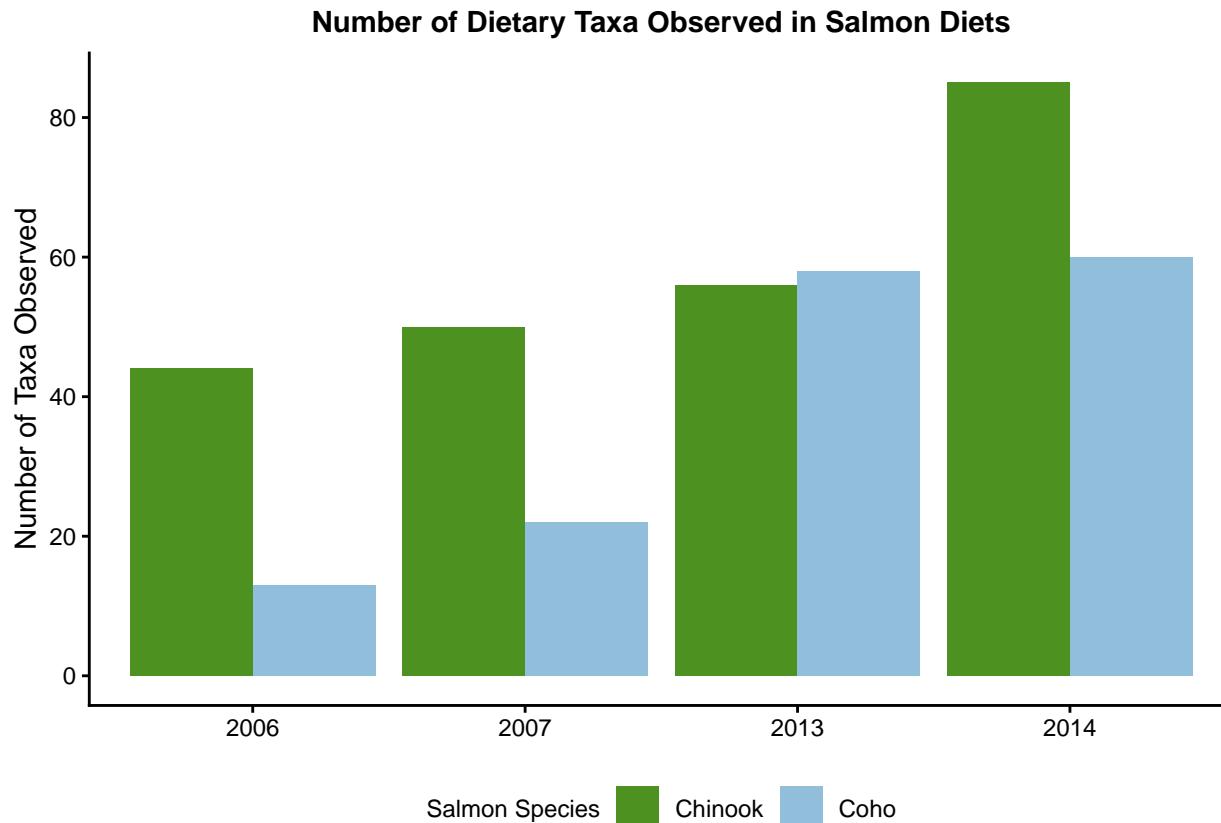


Figure 13: Number of unique taxa consumed by Chinook and Coho salmon in each year samples were collected

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 diet over the two dam conditions, where levels were generally similar between the 2006-2007 and 2013-2014 periods. 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 distribution of the top 10 taxa observed in Chinook (**Figure 14**) and Coho (**Figure 15**) salmon were plotted to assess general trends.

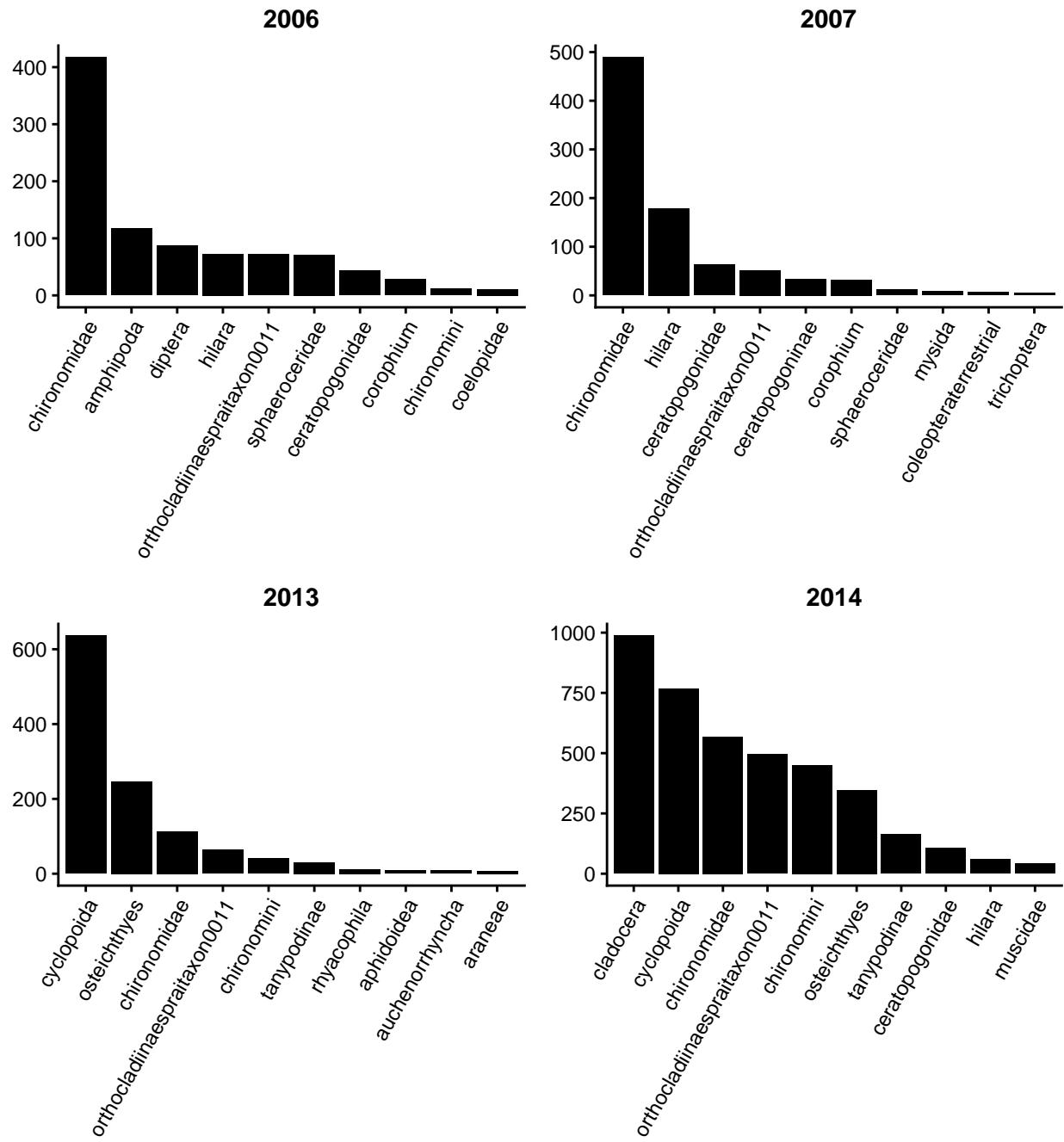


Figure 14: Total counts of the 10 most common dietary taxa each year in Chinook salmon

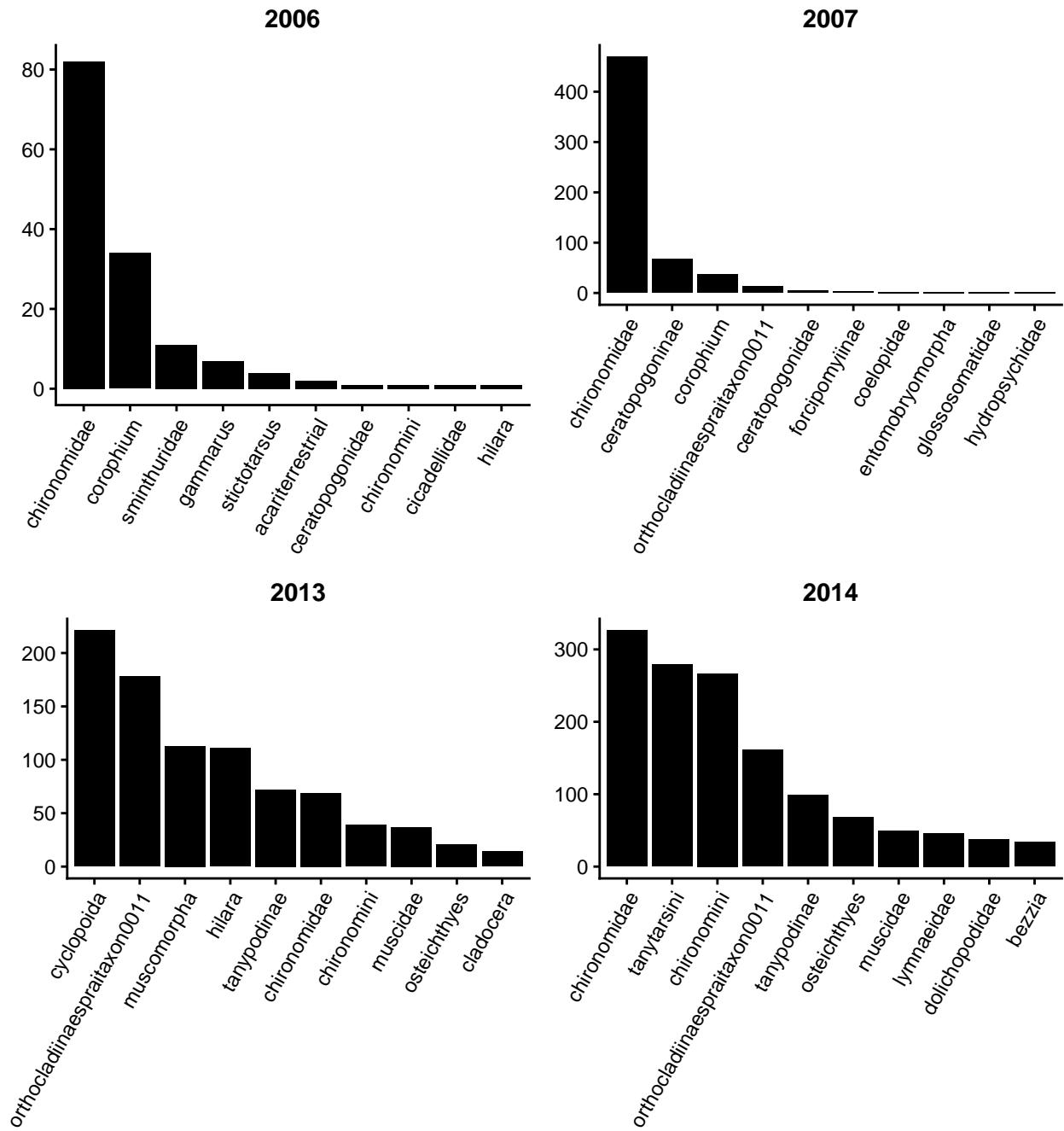


Figure 15: Total counts of the 10 most common dietary taxa each year in Coho salmon

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. Without normalizing the data, no conclusions can be drawn regarding the abundance of food consumed. It is hypothesized that salmon will consume more, and this should be a focus of future research.

To assess how the top taxa were impacted by dam removal, the top ten overall taxa were visualized. These taxa were identified by summing the counts across all years for each taxa. For Chinook salmon, the taxa chironomidae (non-biting midges) are dominant before and after removal (**Figure 16.A**). 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, either at low counts or not at all during removal. 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 16.B**). The overall taxa for Coho salmon are certainly dominated by the pre-dam removal state. Few of the taxa identified here have appreciable counts during the removal. This is likely due to the diversification of their diet after removal.

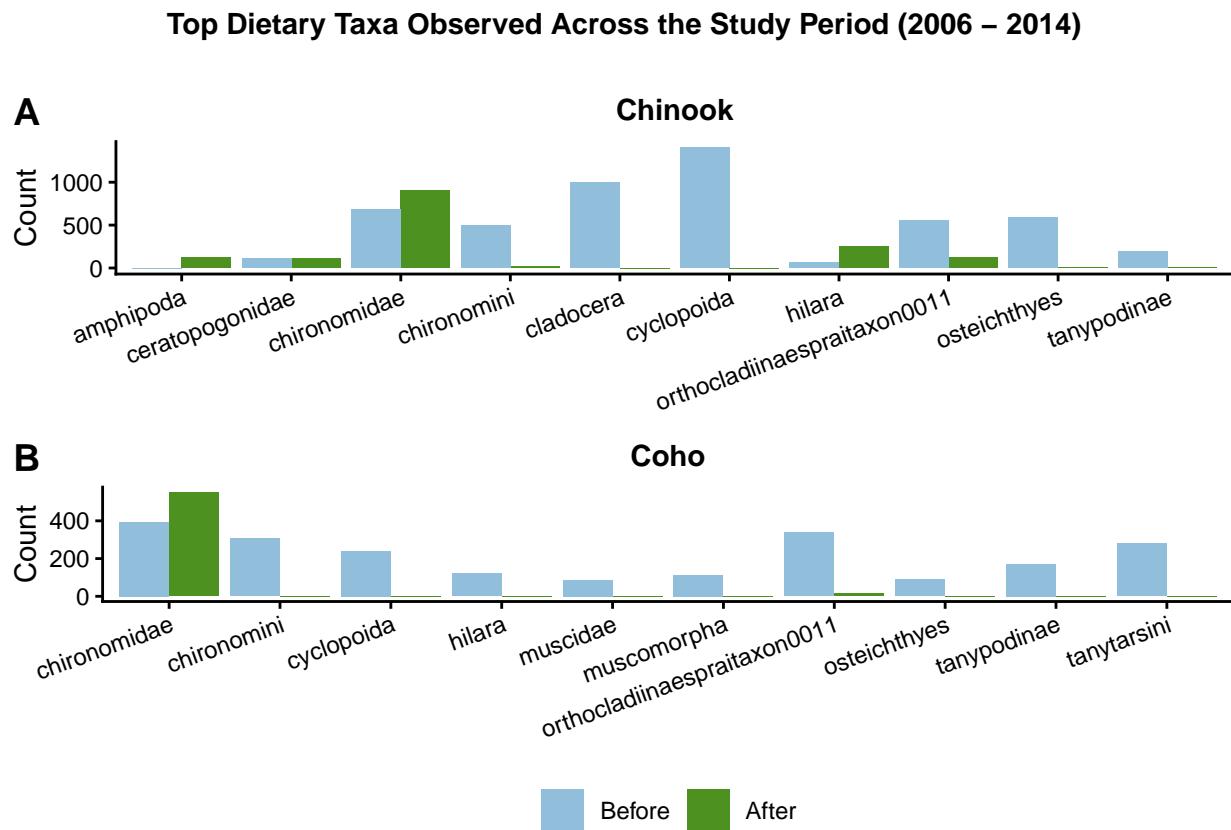


Figure 16: Top taxa for Chinook and Coho salmon before and during dam removal

To better understand the diet of Chinook and Coho during the dam removal, **Figure 17** shows the top taxa observed in both salmon populations during dam removal (2013–2014). Counts of these taxa observed before dam removal are included as well to assess if they were newly introduced into the diet or were being consumed before dam removal.

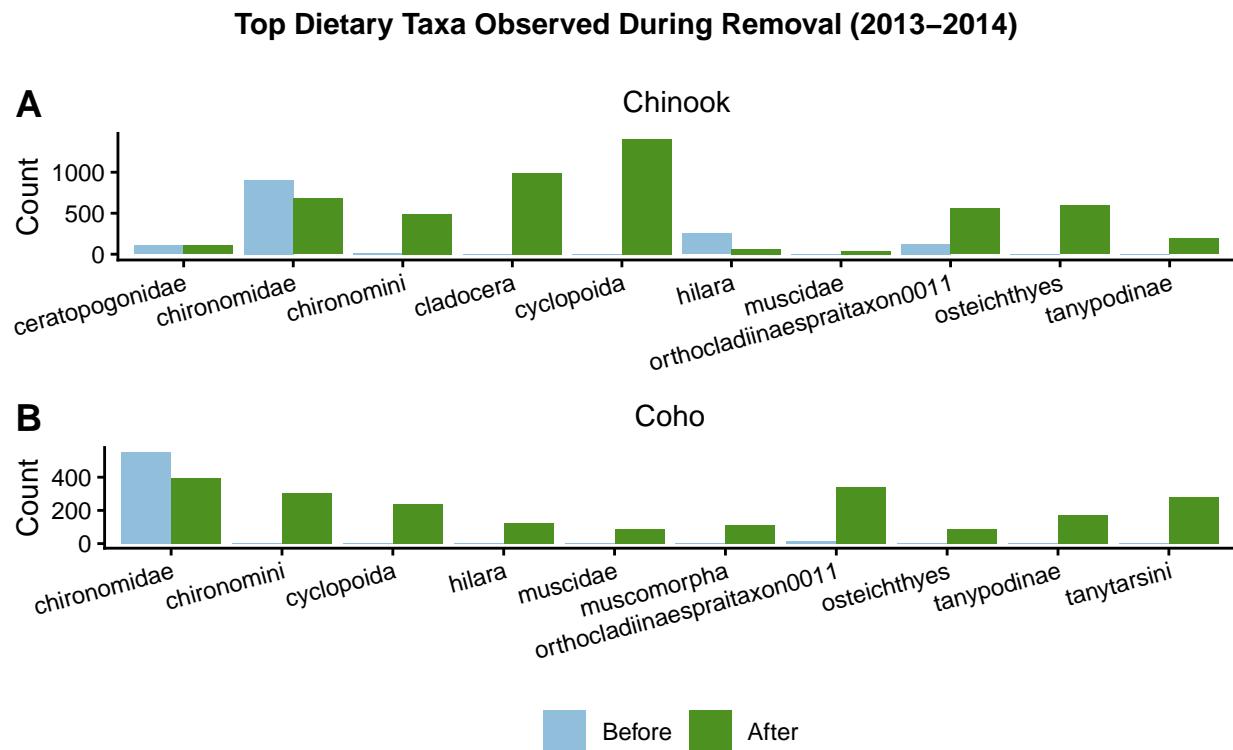


Figure 17: Top taxa for Chinook salmon during dam removal

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. While the time series analysis did find significant monotonic trend in observed discharge levels during all periods analyzed (**Figure 10, Table 9**), average discharge levels during removal were not significantly different from levels before and after removal. However, an ANOVA test confirmed that there was a significant difference ( $p=0.02$ ) between discharge levels observed before and after removal (see **Table 8**). This may be explained by changes in river shape and turbidity as a result of the release of over 100-years worth of accumulated sediment following dam removal (National Park Service, 2016).

Gage height rose significantly during dam removal. A one-way ANOVA test confirmed that gage height was significantly different during dam removal compared to the periods before and after (**Table 8**). A time series analysis confirmed that there were significant monotonic trends during all three periods surrounding dam removal, and that there was a strong positive trend in gage height during removal, and a strong negative trend following its completion (**Figure 10, Table 9**). Ritchie et al. (2018) found that changes in river stage could be attributed to widespread riverbed aggradation. In other words, increased sediment deposition resulted in rising riverbed height and thus higher water levels.

An analysis of suspended sediment load and concentration data found that suspended sediment levels were significantly altered during dam removal. A two-way directional t-test confirmed that suspended sediment concentration was significantly higher ( $p<0.001$ ) during dam removal compared to after dam removal was completed. This change was a result of over 10 million tonnes of trapped sediment in the dams' reservoirs being released throughout the process of dam removal (East et al., 2015). **Figure 7** illustrates that high sediment concentration levels were sustained during dam removal but appear to diminish following its completion. This is likely due to the settlement of suspended sediment over time, while sediment loads continued to peak in the winter during periods of high winter flows and snow melt. Further analysis of sediment bed-load could be interesting to understand how sediment deposits have impacted the morphology of the Elwha River in the years following the completion of the dam removal.

Water quality was not heavily impacted over the time range analyzed, and levels did not exceed unsafe levels (**Figure 7**). It does appear that some nutrient concentrations were elevated after removal at sites that were monitored before dam removal. To fully assess how water quality was impacted by dam removal, significantly more time points 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 (**Figure 13**). There was some overlap in diets, particularly for Chinook salmon between the dam removal states, however, Coho salmon also saw a shift in food sources during the dam removal (**Figure 16**). Between the two species, there was some overlap in taxa consumed, 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. Further investigations of invertebrate density and abundance would clarify if the food these fish are consuming is due to presence and abundance or out of preference due to increased diversity.

It can be seen that the removal of the two dams that previously blocked the Elwha River for nearly a century have positively impacted the physical and biological parameters of the river. Natural conditions, such as streamflow and sediment, are returning to natural conditions and impacts to water quality may be productive for ecological restoration and wildlife conservation. The return of salmon into the river is notable, and it is clear that the dam removal has allowed for diversification of diet.

## VI. Appendix

### VI.A. Data Sources

- Foley, M.M. et al., “Ecological parameters in the Elwha River estuary before and during dam removal,” 2020, version 2.0: U.S. Geological Survey data release, <https://doi.org/10.5066/F75B00N4>.
  - Water quality in the Elwha River estuary, Washington, from 2006 to 2014: <https://www.sciencebase.gov/catalog/item/58f626f8e4b0f2e20545e5ad>
  - Diet of Chinook and coho salmon in the Elwha River estuary, Washington, before and during dam removal: <https://www.sciencebase.gov/catalog/item/5f287fa082cef313ed9e1c96>
- 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>.
- 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>

### VI.B. References

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