Impacts of Dam Removal on the Shenandoah River

https://github.com/lydiecos/WDA-Dam-Removal

Lydie Costes

Figure 1: Dam removal in progress on the North Fork of the Shenandoah River

Contents

List of Tables

List of Figures

1 Rationale and Research Questions

Over the past century, perceptions of dams have gradually changed, as understanding of their serious ecological issues has increased and as existing dams have aged, creating safety concerns and the need for expensive repairs. Dams block the passage of fish and other aquatic species, seriously disrupting life cycles for some species. They also impact water quality and alter natural flow. Increasingly, dam removal is pursued as an option to deal with aging dams and restore rivers.

In this study, I seek to understand how dam removal has impacted the physical and chemical processes of one river, the Neuse River in North Carolina. From 2004-2005, three dams were removed from the Southern Fork of the Shenandoah River (see map below). The gage I will use for these analyses is downstream from these dams and should thus reflect some of the changes in flow and water quality that occurred after these removals.

Below: The red X marks the spot of the McGaheysville Dam, which were removed along with the Knightly Dam and Rockland Dam upstream in 2004-2005. All three dams were located along the south fork of the Shenandoah River, which feeds into the Potomac.

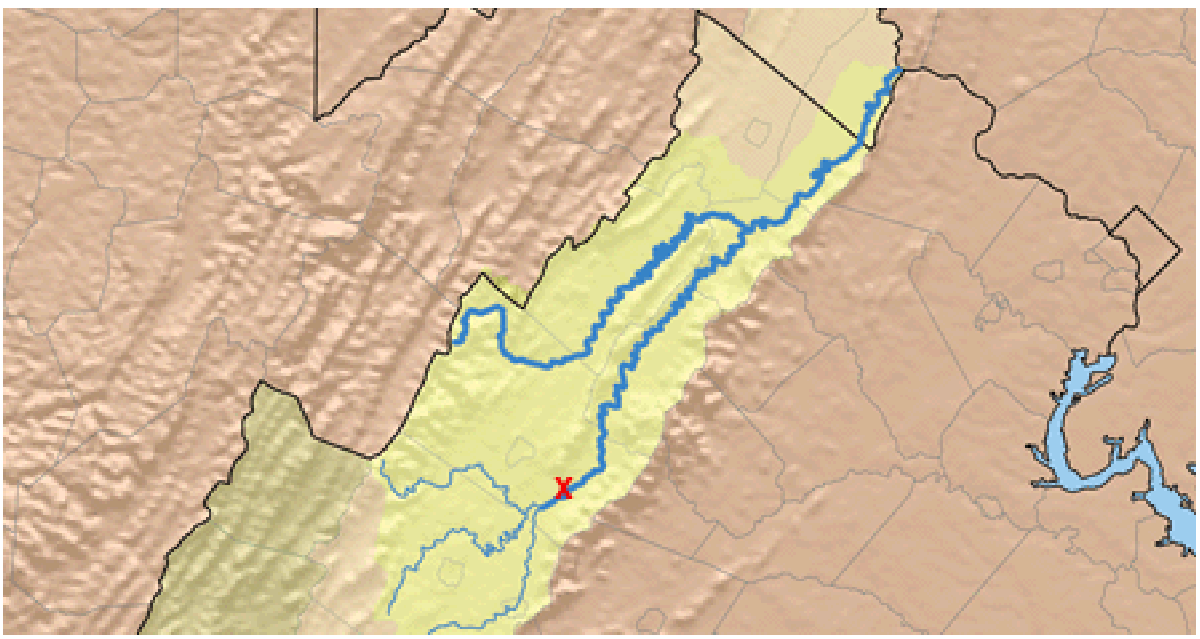

Figure 2: The Shenandoah River, with one of the removed dams marked.

I am interested in both changes in physical process and changes in chemical processes, which can vary widely according to the specific river, its history, and the dam removal process (Foley et al 2017). Dams allow for moderation of flow, often eliminating extreme flooding events. Therefore, dam removal in combination with increasing extreme weather events due to climate change could lead to more extreme and more frequent high flow events. On the other hand, natural river systems and riparian areas can be more resilient to flood events than artificially constructed channels, so true restoration could help mitigate high flow events to some extent.

Changes in water quality are also an area of interest. Large amounts of sediment and minerals built up behind the dam may release quickly after removal, especially if the removal was sudden rather than gradual (Foley et al 2017). Over longer time, water quality is expected to improve because of restored ecological processes.

1. Question 1: Have discharge levels become more extreme or changed since dam removal?
2. Question 2: Has there been a change in release of sediment and nutrients since the dam removal?

2 Dataset Information

The dataset consists of discharge and water quality data from stream gage #01631000, which is located on the South Fork of the Shenandoah River downstream from the three dam removal sites. These data were obtained from USGS StreamStats: https://streamstats.usgs.gov/ss/.

The dataset includes 183 parameters, but these parameters vary widely in terms of how many datapoints were collected. To choose water quality variables, I made a list of the top ten water quality parameters according to the number of observations, and then selected three that I thought would be particularly interesting and informative in light of dam removal. These three were: suspended sediments, nitrogen, and phosphate. Temperature is also included in the exploratory analyses. All of these variables could be expected to change after dam removal.

2.1 Data Wrangling

The data were downloaded as two separate datasets: discharge ('ShenaFlow') and water quality ('ShenaWQ'). Column names were changed from defaults to be more comprehensible. Month and Year columns were added to each dataset.

The discharge dataset was summarized into two dataframes, one by month and the other by year. In both cases, discharge minimum, mean, and maximum were calculated according to the summary unit.

The water quality dataset was transformed into a wider dataset with the four parameters of interest divided into separate columns, instead of being compiled in two columns by characteristic and value. The resulting dataframe was also summarized by month, with minimum, mean, and maximum calculated for each of the four parameters.

The exact timing of dam removal is unknown. Given that three dams were removed between 2004-2005, subsequent analyses that compare "before dam removal" versus "after dam removal" exclude the years 2004-2005 entirely. Most of the water quality variables did not include data for these years anyway.

	vars	n	mean	sd	min	max	range	se
Discharge	1	33452	1602.8971960	2563.3337785	103.00	114000.00	113897.00	14.0150327
Nitrogen_mg.L	1	588	0.9898299	0.4489218	0.01	2.69	2.68	0.0185132
Phosphate_mg.L	2	581	0.2240637	0.2549325	0.00	1.93	1.93	0.0105764
Sediments_mg.L	3	470	54.8588936	150.7588733	0.00	2020.00	2020.00	6.9539883

3 Exploratory Analysis

Below are exploratory plots showing each parameter over time.

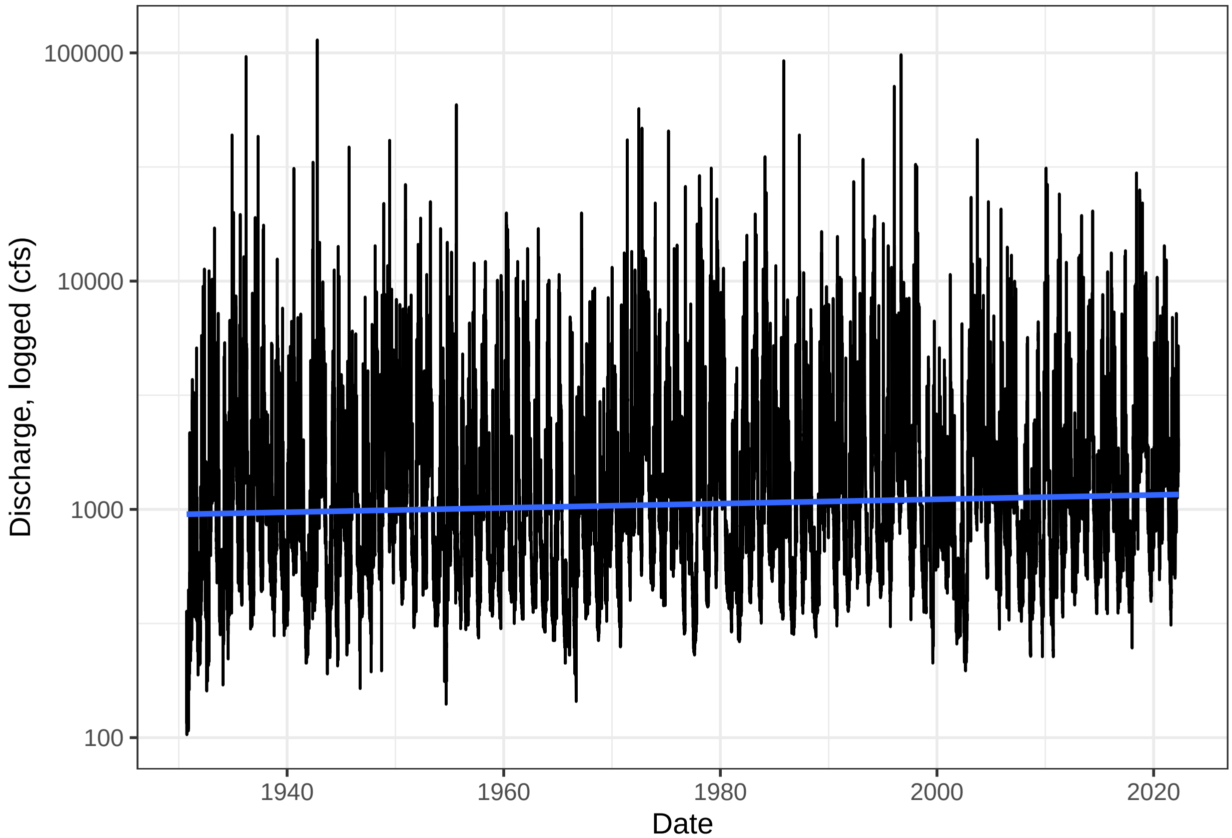

Figure 3: Discharge over time

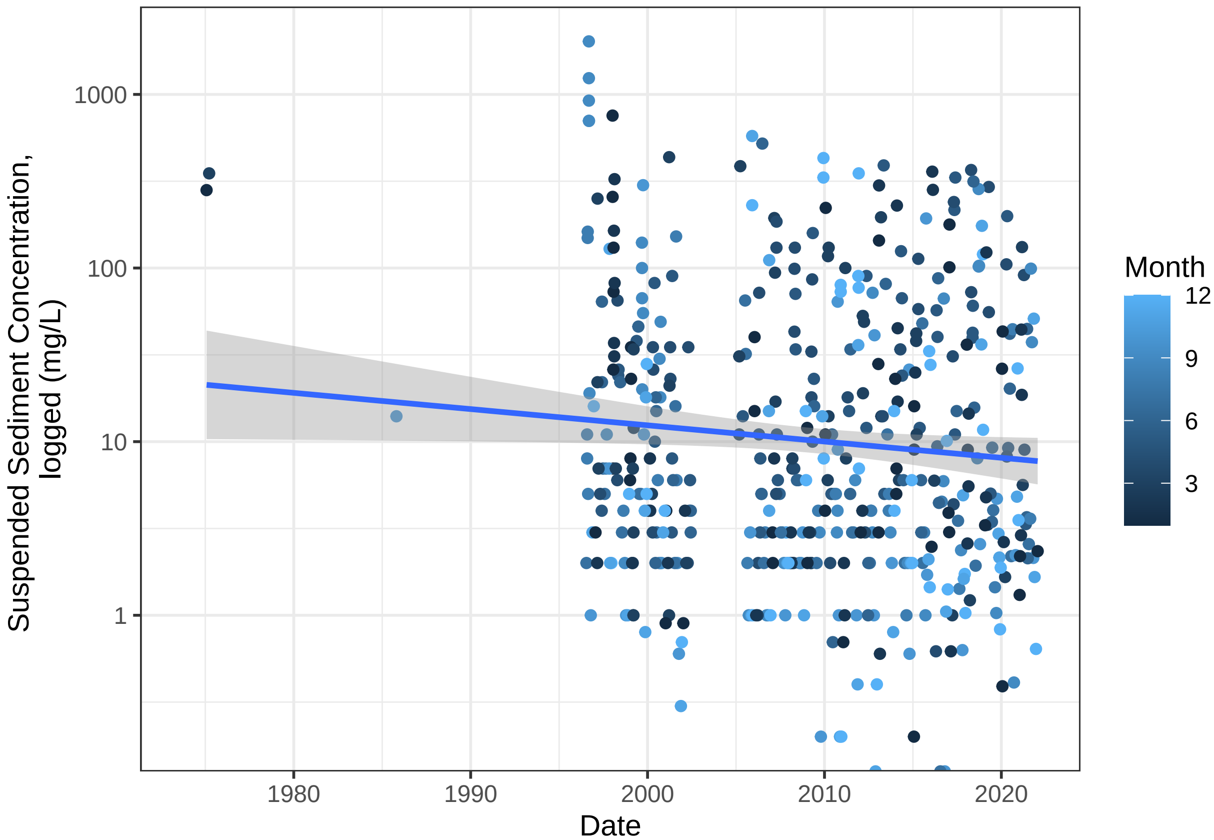

Figure 4: Sediment over time

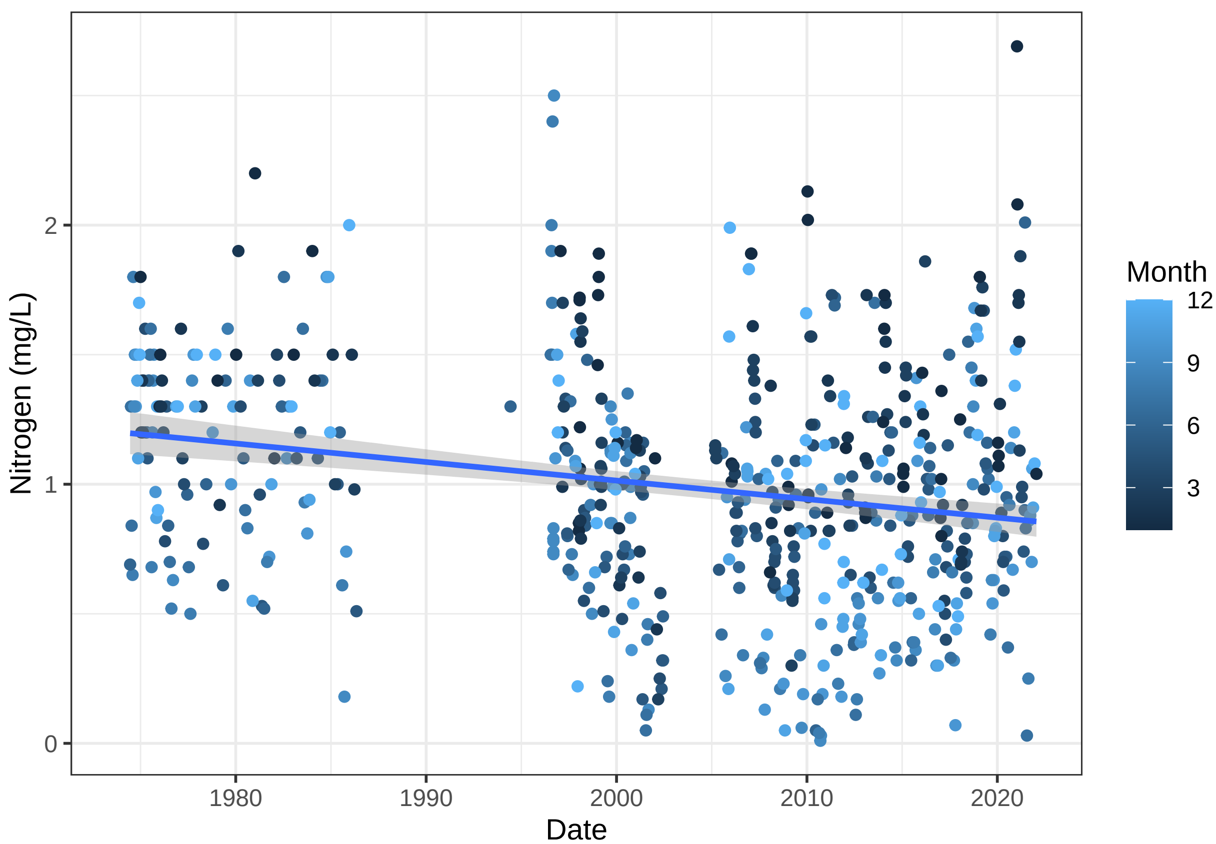

Figure 5: Nitrogen over time

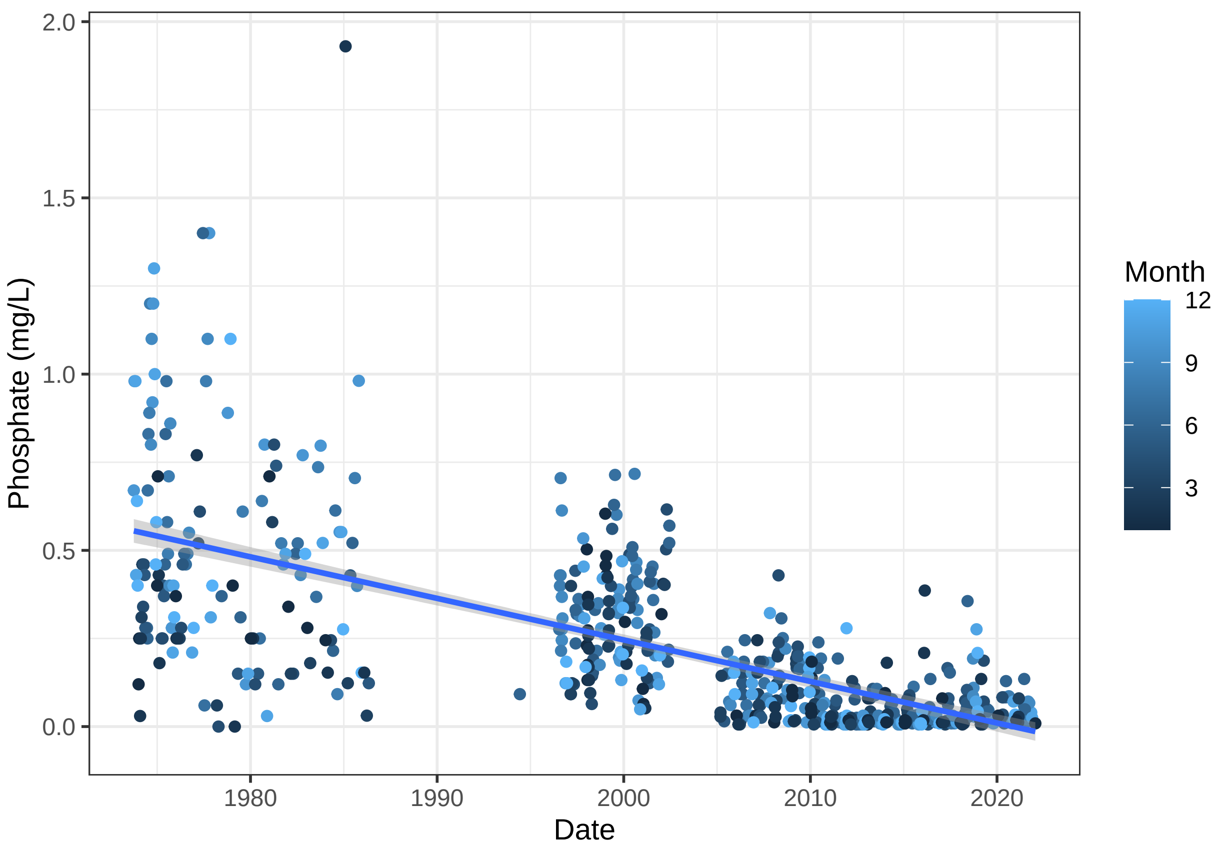

Figure 6: Phosphate over time

4 Analysis

4.1 Part 1: Flow

Question #1: Have discharge extremes increased since the removal of the dams? Has average discharge changed since dam removal?

View minimum and maximum flow by month over time. The y-axis is logged to more easily view the distribution of values.

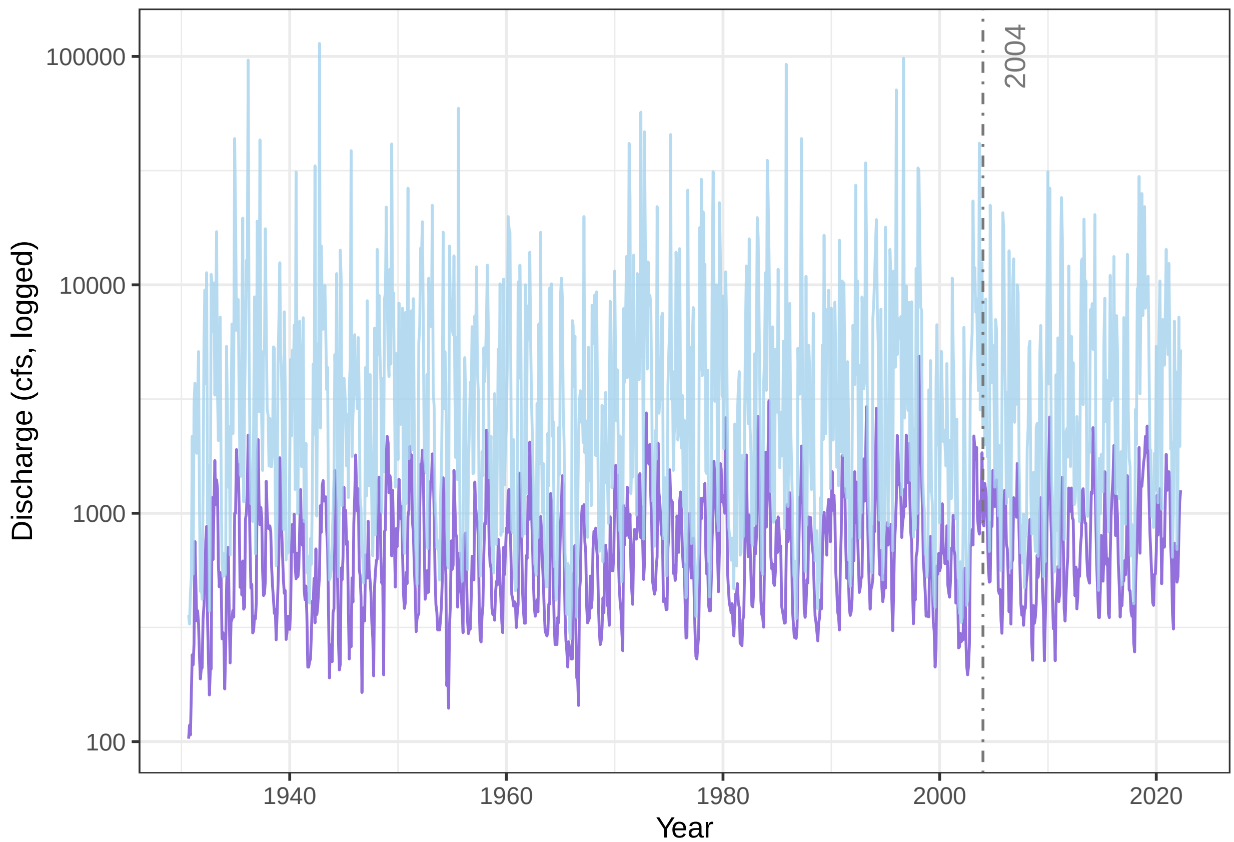

Figure 7: Monthly Minimum and Maximum Discharge Over Time

To better visualize extremes, we'll now look at minimum and maximum flow along with average flow by year. Again, the y-axis is logged to aid with visualization.

These two graphs both suggest that maximum and minimum flows have not gotten more extreme since dam removal; in fact, they appear to be less extreme.

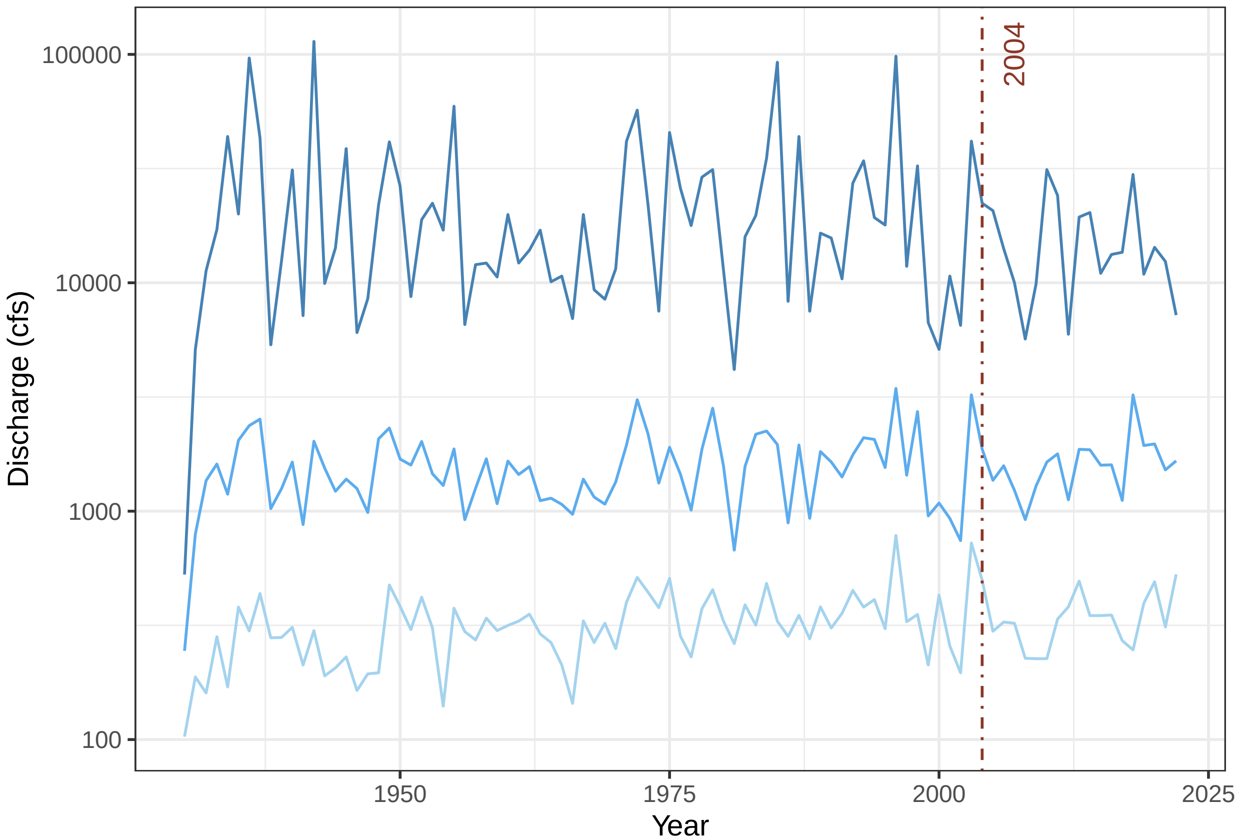

Figure 8: Yearly Minimum, Maximum, and Average Discharge Over Time

Table 2: Summary Statistics for Discharge

	Timeframe	n	mean	sd	min	max	range	se
X1	Before	26764	1594.155	2687.319	103	114000	113897	16.42645
X11	After	5957	1640.320	2009.289	226	31300	31074	26.03326

This table confirms that the river has not experienced more extreme discharge events since dam removal. Additionally, average flow appears to be higher since dam removal. Verify with a t-test:

```
##
##  Welch Two Sample t-test
##
## data:  ShenaFlow.before$Discharge and ShenaFlow.after$Discharge
## t = -1.4997, df = 11246, p-value = 0.1337
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -106.50483   14.17313
## sample estimates:
## mean of x mean of y
##  1594.155  1640.320
```

Flow levels have not been significantly different before (M = 1594.2, SD = 2687.3) versus after (M = 1640.3, SD = 2009.5) the dam removal (p = 0.140, t(11202) = -1.48). Although the extreme discharge events appear to have become less extreme since the dam removal, there has not been a statistically significant change in overall discharge levels. This finding suggests that perhaps without dams, the river is more resilient to high precipitation and drought events.

We can view overall trends by running a time series that takes seasonality into account. In the resulting graph, below, we see general trend before the dam removal in red and after the dam removal in purple.

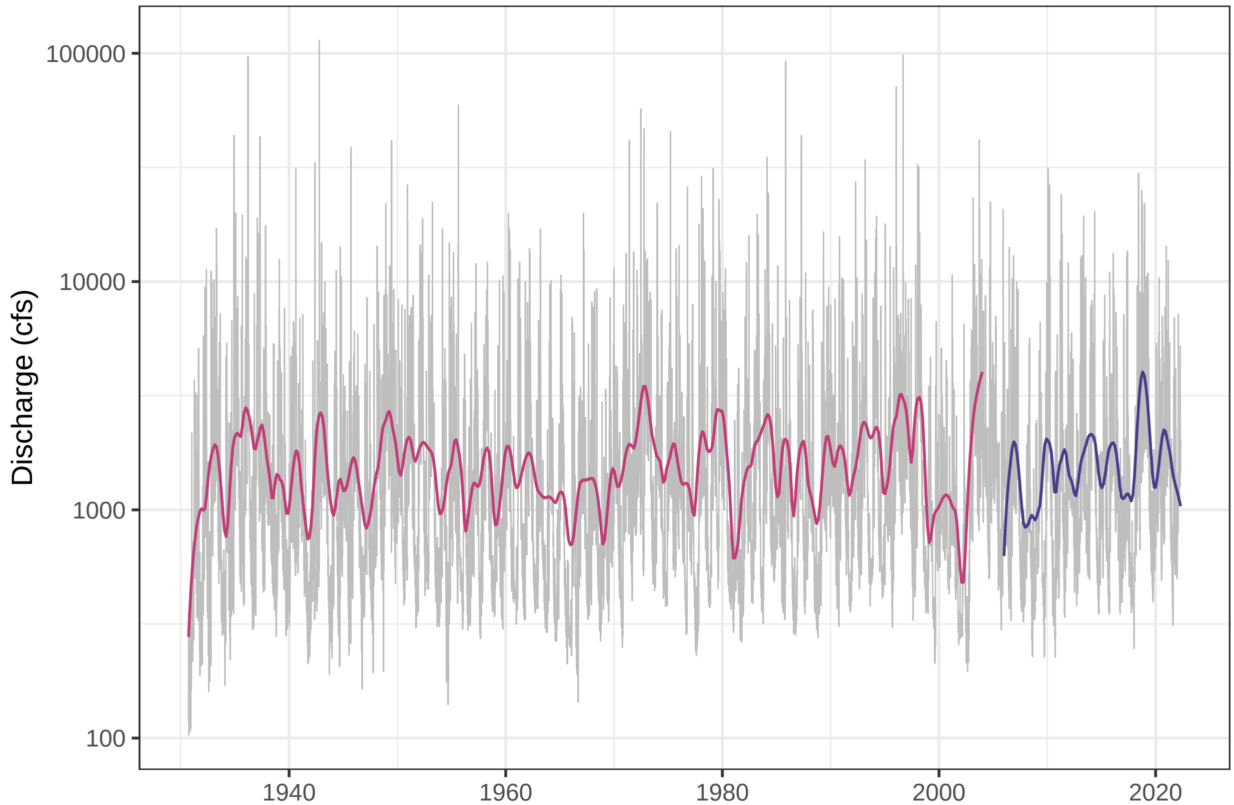

Figure 9: Flow Trends Over Time

4.2 Part 2

Question #2: Has there been a change in release of sediment and nutrients since the dam removal?

4.2.1 Sediment

Have sediment levels changed since dam removal?

View summary statistics comparing sediment levels before versus after dam removal:

Table 3: Summary Statistics for Sediment

	Timeframe	n	mean	sd	min	max	range	se
Sediments_mg.L	Before	137	83.15474	242.94443	0.3	2020	2019.7	20.756144
Sediments_mg.L1	After	320	40.74525	79.73761	0.0	521	521.0	4.457468

Sediment levels appear to be lower on average since dam removal.

Visualize yearly minimum, mean, and maximum sediment levels:

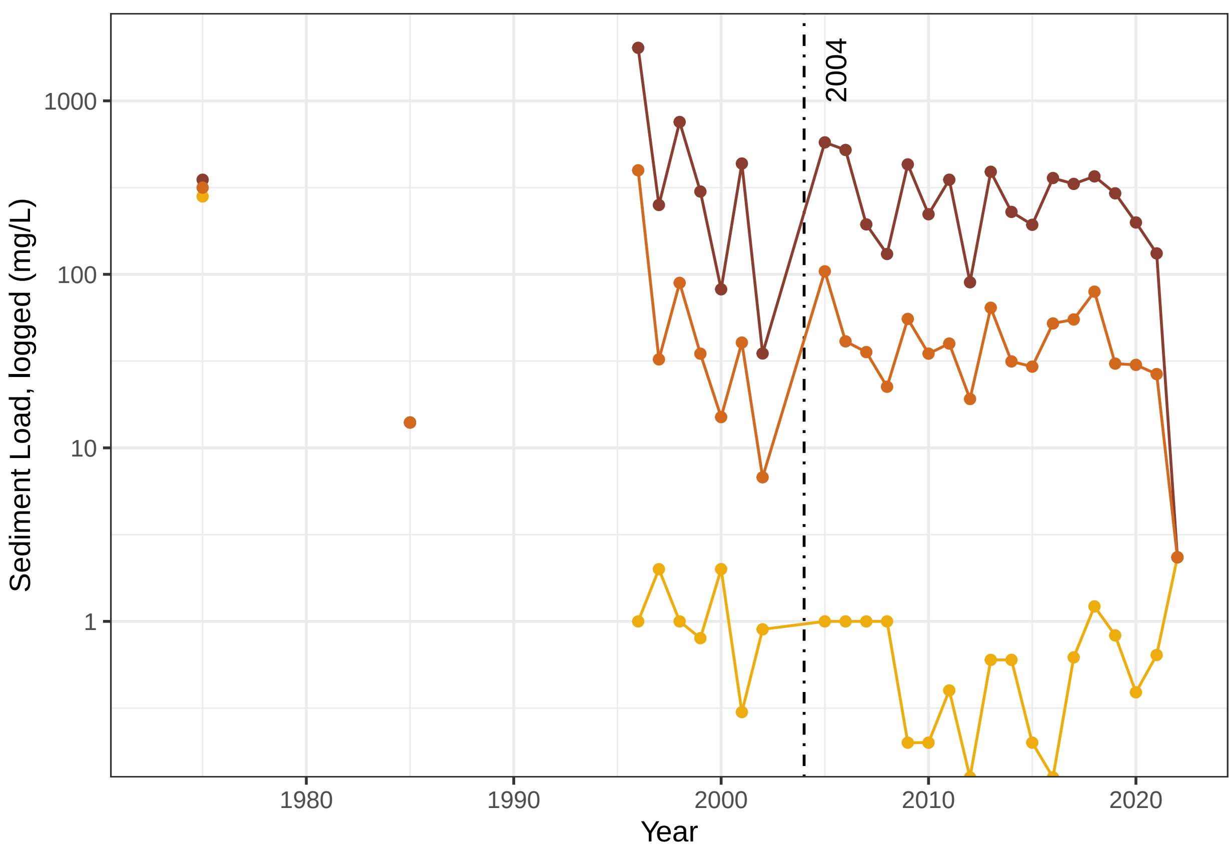

Figure 10: Yearly Minimum, Maximum, and Average Sediment Levels Over Time

Keeping in mind that these values are logged, sediment loads were substantially higher in

1996 than any other year measured. There may have been substantial development or other disruption that year. Further analyses should be considered cautiously because this one outlier year may impact results. We should not exclude it from consideration, because the prior ten years are not available so it could be indicative of a longer trend.

Test whether average sediment has been significantly different before versus after dam removal:

```
##
##  Welch Two Sample t-test
##
## data:  ShenaWQ.before$Sediments_mg.L and ShenaWQ.after$Sediments_mg.L
## t = 1.9977, df = 148.7, p-value = 0.04758
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##   0.4592669 84.3597221
## sample estimates:
## mean of x mean of y
##  83.15474  40.74525
```

Yes, sediment levels have been significantly different ($t(148.63) = 2.00$, $p = 0.047$). Specifically, they have been lower post-dam removal ($M = 40.64$, $SD = 79.63$) compared with pre-dam removal ($M = 83.15$, $SD = 242.94$). This result is surprising because we would expect a large sediment release immediately after dam removal, but the lack of data for the year 2004 may explain the discrepancy. The high sediment loads of 1996 may also have a large impact on this finding.

4.2.2 Nitrogen

Have nitrogen levels changed since dam removal?

View summary statistics comparing nitrogen levels before versus after dam removal:

Table 4: Summary Statistics for Nitrogen

	Timeframe	n	mean	sd	min	max	range	se
Nitrogen_mg.L	Before	254	1.0861811	0.4326022	0.05	2.50	2.45	0.0271439
Nitrogen_mg.L1	After	322	0.9156832	0.4456914	0.01	2.69	2.68	0.0248374

Visualize yearly minimum, mean, and maximum nitrogen levels:

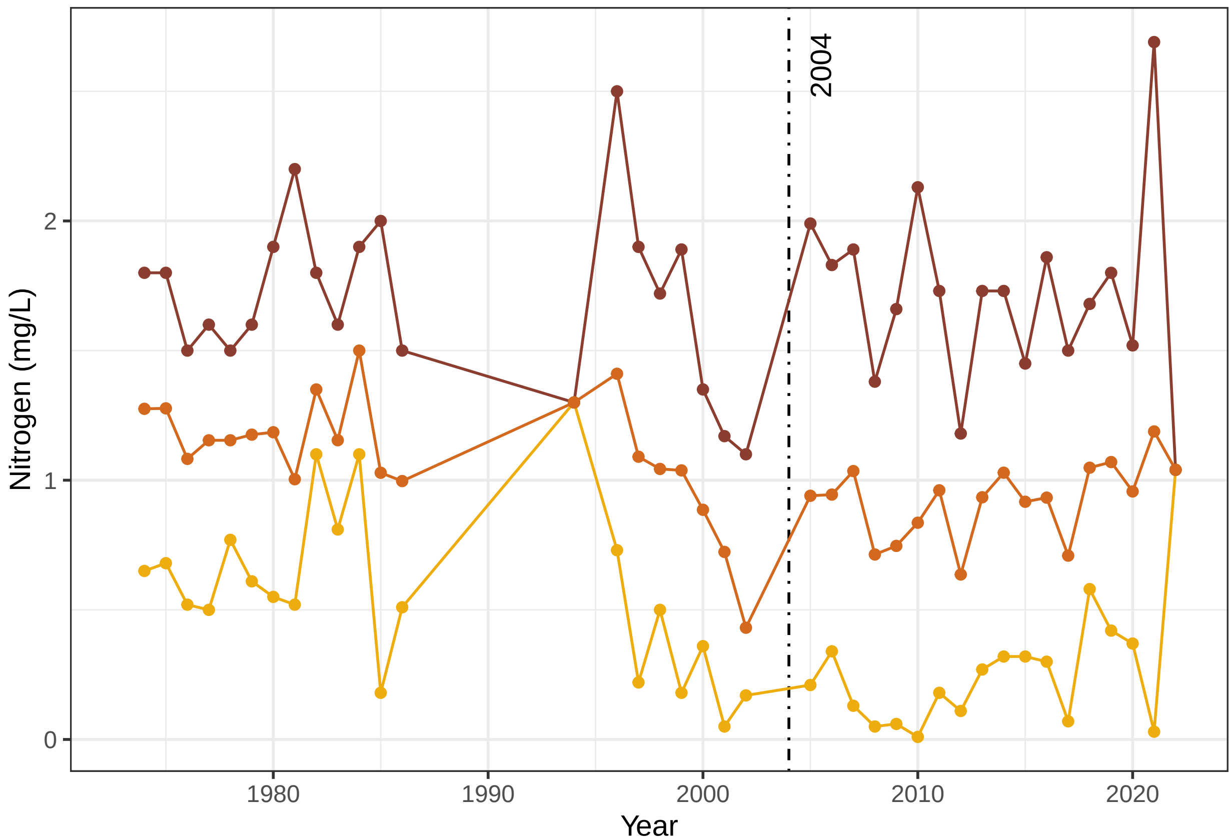

Figure 11: Yearly Minimum, Maximum, and Average Nitrogen Levels Over Time

Check whether average nitrogen levels have changed since dam removal:

```
##
##  Welch Two Sample t-test
##
## data:  ShenaWQ.before$Nitrogen_mg.L and ShenaWQ.after$Nitrogen_mg.L
## t = 4.634, df = 550.09, p-value = 0.000004482
```

```
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  0.09822692 0.24276883
## sample estimates:
## mean of x mean of y
## 1.0861811 0.9156832
```

Yes, nitrogen levels since dam removal ($M = 0.92$, $SD = 0.45$) have been significantly lower ($t(550.8) = 4.56$, $p < 0.001$) compared with nitrogen levels before dam removal ($M = 1.09$, $SD = 0.43$). Nitrogen has a higher potential for denitrification with finer sediments, so perhaps a large influx of sediment immediately after dam removal changed the river floor substantially enough to impact nitrogen levels. On the other hand, a spike occurred in 2021, so nitrogen levels should certainly be followed over a longer time period before drawing definitive conclusions. Nitrogen is highly soluble, so impacts from agriculture and other sources are likely also playing a role.

4.2.3 Phosphate

Have phosphate levels changed since dam removal?

View summary statistics comparing phosphate levels before versus after dam removal:

Table 5: Summary Statistics for Phosphate

	Timeframe	n	mean	sd	min	max	range	se
Phosphate_mg.L	Before	272	0.3984853	0.2743858	0.000	1.930	1.930	0.0166371
Phosphate_mg.L1	After	296	0.0687061	0.0750149	0.006	0.429	0.423	0.0043602

Visualize yearly minimum, mean, and maximum phosphate levels:

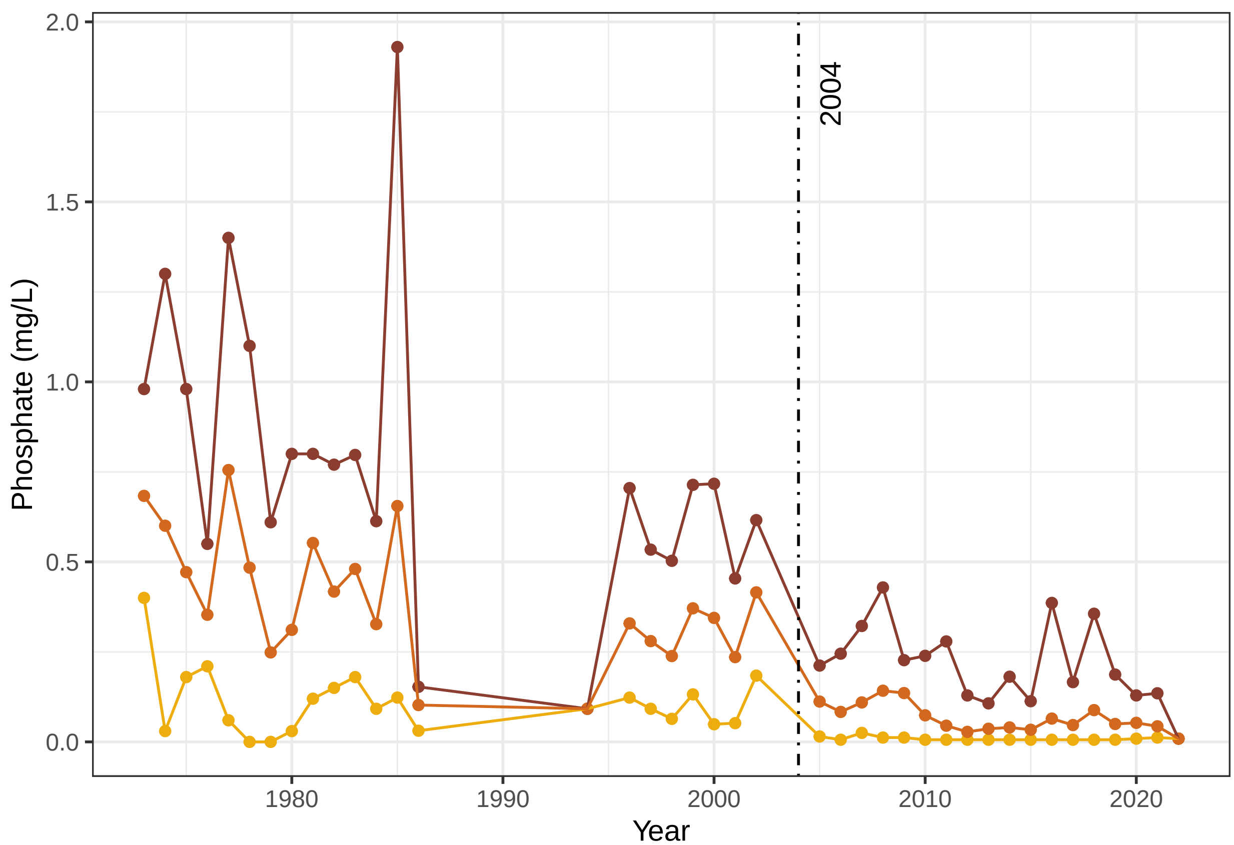

Figure 12: Yearly Minimum, Maximum, and Average Phosphate Levels Over Time

Test whether phosphate levels were different before versus after dam removal:

```
##
##  Welch Two Sample t-test
##
## data:  ShenaWQ.before$Phosphate_mg.L and ShenaWQ.after$Phosphate_mg.L
## t = 19.174, df = 308.17, p-value < 2.2e-16
```

```
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  0.2959370 0.3636214
## sample estimates:
##  mean of x  mean of y
## 0.39848529 0.06870608
```

Phosphate levels have been significantly lower ($t(309.22) = 19.10$, $p < 0.001$) since dam removal ($M = 0.07$, $SD = 0.08$) compared with during the dammed years ($M = 0.40$, $SD = 0.27$). This result is not surprising given our finding with sediment, because phosphate movement through alluvial systems is dependent upon sediment movement (Stanley & Doyle, 2002). However, looking at the graphs, the change in phosphate levels over time are quite striking and began decreasing before dam removal. Changes in regulations of point sources or agricultural practices over time might help explain the dramatic decrease in phosphate levels, though those specific topics were not explored for this project.

5 Summary and Conclusions

These findings suggest that the dam removals on the South Fork of the Shenandoah did impact the flow, sediments, and nutrients of the river downstream. Following these variables over a longer time window would help explain the relative role of the dam removal itself compared with changing climate factors, development, and other river impacts.

Because we did not know the exact timing of the three dam removals and did not have data during these events for all variable, it is important to differentiate between the immediate impacts of a dam removal versus the longer term recovery of the hydrology and ecosystem. In general, dam removal tends to cause a large release of sediment that has built up behind the dam over the years, which may bring high levels of nutrients as well (Stanley & Doyle, 2002).

Flow. Average discharge levels have not changed since dam removal, but the extremes of discharge have been smaller, both less extreme high flow events and less extreme low flow events. This finding is interesting because dams allow control of water, which could hedge against both high and low flow events. On the other hand, restoring natural hydrology makes rivers more resilient to extreme precipitation and drought. The latter seems to be more important in this case, though we cannot eliminate the possibility that perhaps there have not been as extreme precipitation events nor droughts in the past 15 years compared with prior decades. Further monitoring is needed.

Sediment. Sediment levels have been significantly lower since removal. Data are not available for the year 2004, so we do not know the degree of sediment release during and immediately after dam removal. Past research has shown that the high release of sediment from a dam removal can have significant impacts as far as coastal ecosystems (Rubin et al., 2017). In this case at least, it seems that after the initial release of sediment, the restoration of healthy river functions was able to capture and hold a higher level of sediment.

Nutrients. Both nitrogen and phosphate levels have been significantly lower since dam removal. In both cases, the decline in nutrients appears to have begun before dam removal, and we did not assess nutrient levels upstream of the dam over time. Therefore, we cannot say definitively what role the dam itself played. The release and retention of nitrogen and phosphate levels in rivers are affected by sediment levels (Stanley & Doyle, 2002). Thus, the decline in nutrients is likely impacted by the decreased amount of sediment release with changing hydrology as healthy river functions were restored. A better understanding of regulations and land use in the region is needed to understand all factors that may have influenced these decreasing nutrient levels.

In summary, the removal of these three dams on the South Shenandoah appears to have decreased discharge extremes and levels of sediment and nutrients during the 15 years after the 2-year dam removal period. Viewing the data during the actual period of dam removal would be illuminating. Examining other gages, both upstream of the dams and further downstream, could help us understand changing processes. Furthermore, following these parameters over a longer time period will help solidify our understanding of the dam removal, especially with regards to the impacts of climate change and other stressors. Dam removal holds great promise for restoring healthy fluvial systems. Every river is unique, so research must continue to be able to predict the impacts of dam removal and the optimal ways to do so.

6 References

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