Impacts of Dam Removal on the Shenandoah River

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

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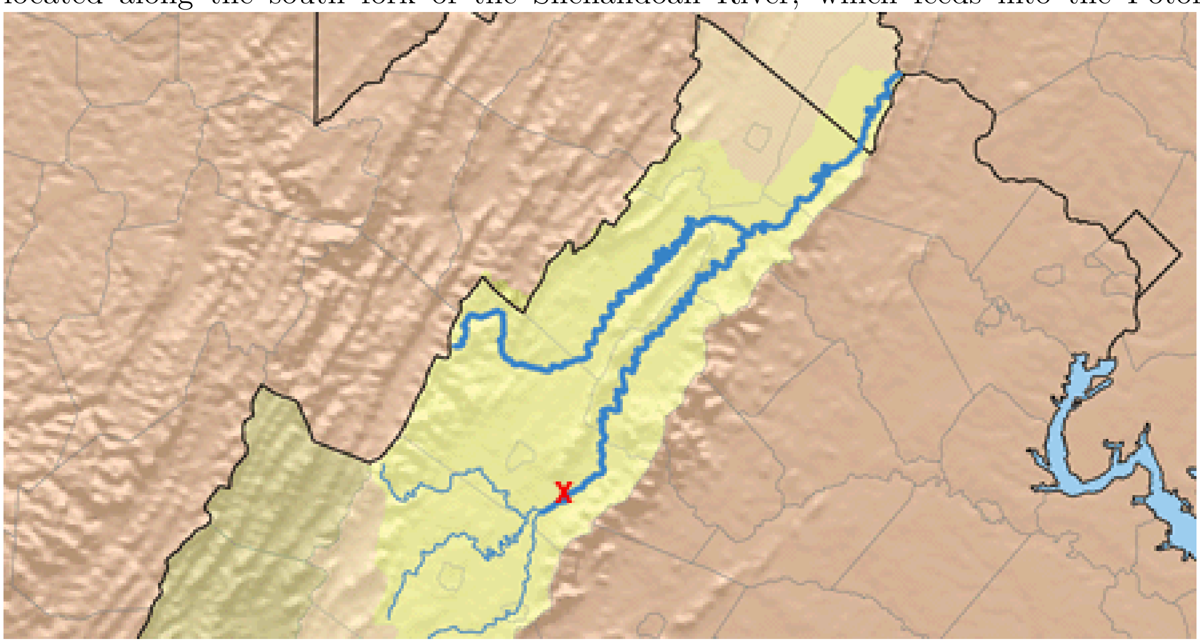
1 Rationale and Research Questions

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, we 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 we are using 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.



We are 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.

1.1 Question 1: Have discharge levels become more extreme since dam removal?

1.2 Question 2: Has there been an increase in release of sediment and nutrients over time?

#+ Have levels steadily increased since dam removal, or did they spike and then stabilize?

2 Dataset Information

```r
# Change column names
names(ShenaFlow)[4:5] <- c("Discharge", "Approval.Code")

# Add month and year column
ShenaFlow <- ShenaFlow %>%
  mutate(Month = month(Date),
         Year = year(Date))

# Check dimensions
dim(ShenaFlow)
```

```
## [1] 33445     7
```

```r
# Check Flow data formats
str(ShenaFlow)
```

```
## 'data.frame':    33445 obs. of  7 variables:
##  $ agency_cd    : chr  "USGS" "USGS" "USGS" "USGS" ...
##  $ site_no      : chr  "01631000" "01631000" "01631000" "01631000" ...
##  $ Date         : Date, format: "1930-09-22" "1930-09-23" ...
##  $ Discharge    : num  242 116 358 243 292 272 258 236 103 178 ...
##  $ Approval.Code: chr  "A" "A" "A" "A" ...
##  $ Month        : num  9 9 9 9 9 9 9 9 9 10 ...
##  $ Year         : num  1930 1930 1930 1930 1930 1930 1930 1930 1930 1930 ...
##  - attr(*, "url")= chr "https://waterservices.usgs.gov/nwis/dv/?site=01631000&format=
##  - attr(*, "siteInfo")='data.frame': 1 obs. of  13 variables:
##   ..$ station_nm          : chr "S F SHENANDOAH RIVER AT FRONT ROYAL, VA"
##   ..$ site_no             : chr "01631000"
##   ..$ agency_cd           : chr "USGS"
##   ..$ timeZoneOffset      : chr "-05:00"
##   ..$ timeZoneAbbreviation: chr "EST"
##   ..$ dec_lat_va          : num 38.9
##   ..$ dec_lon_va          : num -78.2
##   ..$ srs                 : chr "EPSG:4326"
##   ..$ siteTypeCd          : chr "ST"
##   ..$ hucCd               : chr "02070005"
##   ..$ stateCd             : chr "51"
##   ..$ countyCd            : chr "51187"
##   ..$ network             : chr "NWIS"
##  - attr(*, "variableInfo")='data.frame': 1 obs. of  7 variables:
##   ..$ variableCode       : chr "00060"
##   ..$ variableName       : chr "Streamflow, ft&#179;/s"
##   ..$ variableDescription: chr "Discharge, cubic feet per second"
##   ..$ valueType          : chr "Derived Value"
```

```
##   ..$ unit               : chr "ft3/s"
##   ..$ options            : chr "Mean"
##   ..$ noDataValue        : logi NA
##  - attr(*, "disclaimer")= chr "Provisional data are subject to revision. Go to http:/
##  - attr(*, "statisticInfo")='data.frame':    1 obs. of  2 variables:
##   ..$ statisticCd  : chr "00003"
##   ..$ statisticName: chr "Mean"
##  - attr(*, "queryTime")= POSIXct[1:1], format: "2022-04-17 17:44:52"
```

```
# Check Flow data summary
summary(ShenaFlow)
```

```
##   agency_cd          site_no               Date              Discharge
##  Length:33445       Length:33445       Min.   :1930-09-22   Min.   :   103
##  Class :character   Class :character   1st Qu.:1953-08-13   1st Qu.:   544
##  Mode  :character   Mode  :character   Median :1976-07-04   Median :   961
##                                        Mean   :1976-07-04   Mean   :  1603
##                                        3rd Qu.:1999-05-26   3rd Qu.:  1800
##                                        Max.   :2022-04-16   Max.   :114000
##  Approval.Code          Month             Year
##  Length:33445       Min.   : 1.000   Min.   :1930
##  Class :character   1st Qu.: 4.000   1st Qu.:1953
##  Mode  :character   Median : 7.000   Median :1976
##                     Mean   : 6.522   Mean   :1976
##                     3rd Qu.:10.000   3rd Qu.:1999
##                     Max.   :12.000   Max.   :2022
```

```
# Create monthly summary dataset of discharge
ShenaFlow_monthly <- ShenaFlow %>%
  group_by(Year, Month) %>%
  summarise(Discharge_min = min(Discharge),
            Discharge_max = max(Discharge),
            Discharge_mean = mean(Discharge)) %>%
  mutate(Date = as.Date(paste(Year, Month, "1", sep = "-"), format = "%Y-%m-%d"))
```

```
## `summarise()` has grouped output by 'Year'. You can override using the `.groups` argu
```

```
# Check dimensions and summary of dataset
dim(ShenaFlow_monthly)
```

```
## [1] 1100    6
```

```
summary(ShenaFlow_monthly)
```

```
##       Year          Month       Discharge_min    Discharge_max
##  Min.   :1930   Min.   : 1.0   Min.   : 103.0   Min.   :   282
##  1st Qu.:1953   1st Qu.: 3.0   1st Qu.: 397.8   1st Qu.:  1058
##  Median :1976   Median : 6.5   Median : 620.0   Median :  2650
```

```
##  Mean   :1976   Mean   : 6.5   Mean   : 758.7   Mean   :  5400
##  3rd Qu.:1999   3rd Qu.:10.0   3rd Qu.: 987.2   3rd Qu.:  6398
##  Max.   :2022   Max.   :12.0   Max.   :4880.0   Max.   :114000
##  Discharge_mean        Date
##  Min.   :  224.8   Min.   :1930-09-01
##  1st Qu.:  611.2   1st Qu.:1953-07-24
##  Median : 1191.9   Median :1976-06-16
##  Mean   : 1605.7   Mean   :1976-06-16
##  3rd Qu.: 2120.7   3rd Qu.:1999-05-08
##  Max.   :10597.5   Max.   :2022-04-01
```

```
# Create yearly summary dataset of discharge
ShenaFlow_yearly <- ShenaFlow %>%
  group_by(Year) %>%
  summarise(Discharge_min = min(Discharge),
            Discharge_max = max(Discharge),
            Discharge_mean = mean(Discharge))
# Check dimensions and summary of dataset
dim(ShenaFlow_yearly)
```

```
## [1] 93  4
```

```
summary(ShenaFlow_yearly)
```

```
##       Year      Discharge_min   Discharge_max    Discharge_mean
##  Min.   :1930   Min.   :103.0   Min.   :   528   Min.   : 244.6
##  1st Qu.:1953   1st Qu.:263.0   1st Qu.: 10000   1st Qu.:1152.8
##  Median :1976   Median :316.0   Median : 15700   Median :1567.3
##  Mean   :1976   Mean   :326.7   Mean   : 22030   Mean   :1592.6
##  3rd Qu.:1999   3rd Qu.:380.0   3rd Qu.: 26500   3rd Qu.:1904.0
##  Max.   :2022   Max.   :783.0   Max.   :114000   Max.   :3446.6
```

```
# Convert WQ to wider dataframe with characteristics of interest
ShenaWQ_processed <- ShenaWQ %>%
  select(MonitoringLocationIdentifier, ActivityStartDate, HydrologicCondition,
         CharacteristicName, ResultMeasureValue) %>%
  mutate(Month = month(ActivityStartDate),
         Year = year(ActivityStartDate),
         Variable = case_when(CharacteristicName == "Suspended Sediment Concentration (S
                              CharacteristicName == "Inorganic nitrogen (nitrate and nit
                              CharacteristicName == "Orthophosphate" ~ "Phosphate_mg.L",
                              CharacteristicName == "Temperature, water" ~ "Temp_C")) %>
  select(-CharacteristicName) %>%
  pivot_wider(names_from = "Variable", values_from = "ResultMeasureValue") %>%
  unnest(cols = c(Sediments_mg.L, Nitrogen_mg.L, Phosphate_mg.L, Temp_C))
```

```
## Warning: Values are not uniquely identified; output will contain list-cols.
```

```
## * Use `values_fn = list` to suppress this warning.
## * Use `values_fn = length` to identify where the duplicates arise
## * Use `values_fn = {summary_fun}` to summarise duplicates
```

```
str(ShenaWQ_processed)
```

```
## tibble [774 x 10] (S3: tbl_df/tbl/data.frame)
##  $ MonitoringLocationIdentifier: chr [1:774] "USGS-01631000" "USGS-01631000" "USGS-01
##  $ ActivityStartDate           : Date[1:774], format: "1970-06-21" "1970-05-03" ...
##  $ HydrologicCondition         : chr [1:774] "Not determined" "Not determined" "Not d
##  $ Month                       : num [1:774] 6 5 7 4 8 6 8 6 5 7 ...
##  $ Year                        : num [1:774] 1970 1970 1971 1970 1974 ...
##  $ NA                          :List of 774
##   ..$ : num [1:5] 44 7.8 160 341 13
##   ..$ : num [1:5] 193 7.4 91 6.6 26
##   ..$ : num [1:5] 150 41 7.9 12 340
##   ..$ : num [1:5] 23 173 82 7.3 6
##   ..$ : num [1:4] 14 343 42 160
##   ..$ : num [1:5] 44 332 11 160 7.5
##   ..$ : num [1:4] 13 41 369 160
##   ..$ : num [1:5] 6.9 255 120 34 8.5
##   ..$ : num [1:5] 10 33 120 7.8 290
##   ..$ : num [1:5] 320 7.5 130 35 11
##   ..$ : num [1:4] 342 14 170 43
##   ..$ : num [1:5] 164 25 4.6 82 7.6
##   ..$ : num [1:5] 12 35 140 416 8.2
##   ..$ : num [1:4] 238 120 34 8.4
##   ..$ : num [1:4] 120 205 32 8.5
##   ..$ : num [1:4] 295 140 37 11
##   ..$ : num [1:5] 141 35 13 348 8.2
##   ..$ : num [1:5] 7.4 110 30 7.8 220
##   ..$ : num [1:5] 43 7.8 160 365 14
##   ..$ : num [1:5] 22 6.6 7.4 82 195
##   ..$ : num [1:5] 149 7.2 65 18 4.8
##   ..$ : num [1:5] 44 170 8.9 15 385
##   ..$ : num [1:5] 8.8 330 39 155 14
##   ..$ : num [1:5] 263 8.7 32 10 121
##   ..$ : num [1:4] 140 300 36 11
##   ..$ : num [1:4] 170 15 44 320
##   ..$ : num [1:5] 42 170 15 7.5 360
##   ..$ : num [1:5] 211 7.4 28 100 7.3
##   ..$ : num [1:5] 40 14 9.1 158 383
##   ..$ : num [1:4] 12 42 150 371
##   ..$ : num [1:5] 180 7.9 390 44 16
##   ..$ : num [1:4] 11 36 140 240
```

```
##   ..$ : num [1:5] 340 7.8 140 13 35
##   ..$ : num [1:5] 277 8 10 35 130
##   ..$ : num [1:5] 18 4.2 155 7.3 62
##   ..$ : num [1:5] 7.6 340 42 11 150
##   ..$ : num [1:5] 8.1 298 123 31 11
##   ..$ : num [1:5] 140 43 8.9 7.5 304
##   ..$ : num [1:5] 310 8.3 140 36 11
##   ..$ : num [1:5] 8.9 30 110 7.7 298
##   ..$ : num [1:5] 280 32 9.5 8 120
##   ..$ : num [1:5] 120 8.2 35 7.9 255
##   ..$ : num [1:5] 9.1 39 155 14 317
##   ..$ : num [1:5] 15 160 40 7.9 340
##   ..$ : num [1:5] 8.2 382 150 37 14
##   ..$ : num [1:5] 28 7.6 100 235 7.5
##   ..$ : num [1:5] 12 7.7 37 355 140
##   ..$ : num [1:5] 302 8.8 10 130 37
##   ..$ : num [1:5] 83 7.7 24 5.6 185
##   ..$ : num [1:5] 7.8 319 130 34 11
##   ..$ : num [1:5] 8 367 160 40 15
##   ..$ : num [1:4] 160 381 40 14
##   ..$ : num [1:4] 12 37 140 268
##   ..$ : num [1:4] 124 8.4 100 27
##   ..$ : num [1:5] 8.3 349 41 12 150
##   ..$ : num [1:5] 140 35 13 343 8.6
##   ..$ : num [1:5] 7.8 140 370 38 12
##   ..$ : num [1:5] 270 7.5 130 34 11
##   ..$ : num [1:5] 130 300 7.5 36 9.6
##   ..$ : num [1:2] 175 6.6
##   ..$ : num [1:5] 7.5 310 140 11 38
##   ..$ : num [1:5] 10 121 32 265 8.7
##   ..$ : num [1:5] 25 9 100 273 8.4
##   ..$ : num [1:2] 218 7
##   ..$ : num [1:5] 130 7.7 36 10 289
##   ..$ : num [1:4] 9.7 120 250 32
##   ..$ : num [1:5] 45 13 7.8 170 370
##   ..$ : num [1:2] 360 8.4
##   ..$ : num [1:2] 137 7.8
##   ..$ : num [1:5] 10 34 290 7.4 130
##   ..$ : num [1:5] 220 7.8 98 27 7.5
##   ..$ : num [1:5] 195 6.6 7.3 23 84
##   ..$ : num [1:5] 8.8 27 100 260 7.6
##   ..$ : num [1:2] 206 7.8
##   ..$ : num [1:5] 100 30 235 7.6 6.4
##   ..$ : num [1:4] 13 40 150 330
##   ..$ : num [1:5] 264 8.8 111 29 9.4
```

```
##   ..$ : num [1:5] 330 7.5 150 8.8 45
##   ..$ : num [1:4] 330 140 38 12
##   ..$ : num [1:5] 194 7.7 88.3 24.1 6.81
##   ..$ : num [1:5] 194 90.8 7.9 25 6.9
##   ..$ : num [1:2] 7.9 313
##   ..$ : num [1:4] 14 40 340 160
##   ..$ : num [1:5] 13 330 8 160 43
##   ..$ : num [1:2] 7.8 318
##   ..$ : num [1:5] 8.6 298 132 32.7 12.3
##   ..$ : num [1:5] 275 7.7 130 34 10
##   ..$ : num [1:5] 7.5 14 300 140 32
##   ..$ : num [1:5] 200 90 25 7.3 6.6
##   ..$ : num [1:2] 349 8.4
##   ..$ : num [1:2] 300 8.6
##   ..$ : num [1:5] 368 8.7 174 45 15
##   ..$ : num [1:5] 196 7.4 86 25 5.7
##   ..$ : num [1:5] 10 8 130 37 288
##   ..$ : num [1:5] 11 7.7 110 27 255
##   ..$ : num [1:5] 7.8 34 307 130 11
##   ..$ : num [1:5] 41 140 10 285 7.4
##   ..$ : num [1:2] 332 8.3
##   ..$ : num [1:5] 13 7.7 160 41 360
##   .. [list output truncated]
##  $ Nitrogen_mg.L              : num [1:774] NA NA NA NA 1.8 NA 0.65 0.69 NA NA ...
##  $ Temp_C                     : num [1:774] 25 20 25 16 23 24 24 23 13 28 ...
##  $ Phosphate_mg.L             : num [1:774] NA NA NA NA 1.2 NA 0.89 0.28 NA NA ...
##  $ Sediments_mg.L             : num [1:774] NA NA NA NA NA NA NA NA NA NA ...
```

```
# Rename the date column
names(ShenaWQ_processed)[2] <- "Date"

# Check the dimensions
dim(ShenaWQ_processed)
```

```
## [1] 774  10
```

```
# Check the summary
summary(ShenaWQ_processed)
```

```
##  MonitoringLocationIdentifier      Date             HydrologicCondition
##  Length:774                   Min.   :1967-10-30   Length:774
##  Class :character             1st Qu.:1975-07-04   Class :character
##  Mode  :character             Median :2000-05-27   Mode  :character
##                               Mean   :1996-06-08
##                               3rd Qu.:2012-06-24
##                               Max.   :2022-03-29
```

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##
##
##
##      Month            Year      NA.Length  NA.Class  NA.Mode Nitrogen_mg.L
##  Min.   : 1.000   Min.   :1967   5         -none-   numeric    Min.   :0.0100
##  1st Qu.: 3.000   1st Qu.:1975   5         -none-   numeric    1st Qu.:0.6800
##  Median : 6.000   Median :2000   5         -none-   numeric    Median :0.9900
##  Mean   : 6.216   Mean   :1996   5         -none-   numeric    Mean   :0.9912
##  3rd Qu.: 9.000   3rd Qu.:2012   4         -none-   numeric    3rd Qu.:1.3000
##  Max.   :12.000   Max.   :2022   5         -none-   numeric    Max.   :2.6900
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##      Temp_C       Phosphate_mg.L   Sediments_mg.L
##  Min.   :-0.10   Min.   :0.0000   Min.   :   0.000
##  1st Qu.: 7.00   1st Qu.:0.0310   1st Qu.:   2.575
##  Median :13.70   Median :0.1440   Median :   7.000
##  Mean   :14.29   Mean   :0.2251   Mean   :  55.223
##  3rd Qu.:22.00   3rd Qu.:0.3310   3rd Qu.:  37.850
##  Max.   :30.50   Max.   :1.9300   Max.   :2020.000
##  NA's   :7       NA's   :195      NA's   :308
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```r
# Check WQ data formats
str(ShenaWQ_processed)
```

```
## tibble [774 x 10] (S3: tbl_df/tbl/data.frame)
##  $ MonitoringLocationIdentifier: chr [1:774] "USGS-01631000" "USGS-01631000" "USGS-01
##  $ Date                        : Date[1:774], format: "1970-06-21" "1970-05-03" ...
##  $ HydrologicCondition         : chr [1:774] "Not determined" "Not determined" "Not d
##  $ Month                       : num [1:774] 6 5 7 4 8 6 8 6 5 7 ...
##  $ Year                        : num [1:774] 1970 1970 1971 1970 1974 ...
##  $ NA                          :List of 774
##   ..$ : num [1:5] 44 7.8 160 341 13
##   ..$ : num [1:5] 193 7.4 91 6.6 26
##   ..$ : num [1:5] 150 41 7.9 12 340
##   ..$ : num [1:5] 23 173 82 7.3 6
##   ..$ : num [1:4] 14 343 42 160
##   ..$ : num [1:5] 44 332 11 160 7.5
##   ..$ : num [1:4] 13 41 369 160
##   ..$ : num [1:5] 6.9 255 120 34 8.5
##   ..$ : num [1:5] 10 33 120 7.8 290
##   ..$ : num [1:5] 320 7.5 130 35 11
##   ..$ : num [1:4] 342 14 170 43
```

```
##   ..$ : num [1:5] 164 25 4.6 82 7.6
##   ..$ : num [1:5] 12 35 140 416 8.2
##   ..$ : num [1:4] 238 120 34 8.4
##   ..$ : num [1:4] 120 205 32 8.5
##   ..$ : num [1:4] 295 140 37 11
##   ..$ : num [1:5] 141 35 13 348 8.2
##   ..$ : num [1:5] 7.4 110 30 7.8 220
##   ..$ : num [1:5] 43 7.8 160 365 14
##   ..$ : num [1:5] 22 6.6 7.4 82 195
##   ..$ : num [1:5] 149 7.2 65 18 4.8
##   ..$ : num [1:5] 44 170 8.9 15 385
##   ..$ : num [1:5] 8.8 330 39 155 14
##   ..$ : num [1:5] 263 8.7 32 10 121
##   ..$ : num [1:4] 140 300 36 11
##   ..$ : num [1:4] 170 15 44 320
##   ..$ : num [1:5] 42 170 15 7.5 360
##   ..$ : num [1:5] 211 7.4 28 100 7.3
##   ..$ : num [1:5] 40 14 9.1 158 383
##   ..$ : num [1:4] 12 42 150 371
##   ..$ : num [1:5] 180 7.9 390 44 16
##   ..$ : num [1:4] 11 36 140 240
##   ..$ : num [1:5] 340 7.8 140 13 35
##   ..$ : num [1:5] 277 8 10 35 130
##   ..$ : num [1:5] 18 4.2 155 7.3 62
##   ..$ : num [1:5] 7.6 340 42 11 150
##   ..$ : num [1:5] 8.1 298 123 31 11
##   ..$ : num [1:5] 140 43 8.9 7.5 304
##   ..$ : num [1:5] 310 8.3 140 36 11
##   ..$ : num [1:5] 8.9 30 110 7.7 298
##   ..$ : num [1:5] 280 32 9.5 8 120
##   ..$ : num [1:5] 120 8.2 35 7.9 255
##   ..$ : num [1:5] 9.1 39 155 14 317
##   ..$ : num [1:5] 15 160 40 7.9 340
##   ..$ : num [1:5] 8.2 382 150 37 14
##   ..$ : num [1:5] 28 7.6 100 235 7.5
##   ..$ : num [1:5] 12 7.7 37 355 140
##   ..$ : num [1:5] 302 8.8 10 130 37
##   ..$ : num [1:5] 83 7.7 24 5.6 185
##   ..$ : num [1:5] 7.8 319 130 34 11
##   ..$ : num [1:5] 8 367 160 40 15
##   ..$ : num [1:4] 160 381 40 14
##   ..$ : num [1:4] 12 37 140 268
##   ..$ : num [1:4] 124 8.4 100 27
##   ..$ : num [1:5] 8.3 349 41 12 150
##   ..$ : num [1:5] 140 35 13 343 8.6
```

```
##   ..$ : num [1:5] 7.8 140 370 38 12
##   ..$ : num [1:5] 270 7.5 130 34 11
##   ..$ : num [1:5] 130 300 7.5 36 9.6
##   ..$ : num [1:2] 175 6.6
##   ..$ : num [1:5] 7.5 310 140 11 38
##   ..$ : num [1:5] 10 121 32 265 8.7
##   ..$ : num [1:5] 25 9 100 273 8.4
##   ..$ : num [1:2] 218 7
##   ..$ : num [1:5] 130 7.7 36 10 289
##   ..$ : num [1:4] 9.7 120 250 32
##   ..$ : num [1:5] 45 13 7.8 170 370
##   ..$ : num [1:2] 360 8.4
##   ..$ : num [1:2] 137 7.8
##   ..$ : num [1:5] 10 34 290 7.4 130
##   ..$ : num [1:5] 220 7.8 98 27 7.5
##   ..$ : num [1:5] 195 6.6 7.3 23 84
##   ..$ : num [1:5] 8.8 27 100 260 7.6
##   ..$ : num [1:2] 206 7.8
##   ..$ : num [1:5] 100 30 235 7.6 6.4
##   ..$ : num [1:4] 13 40 150 330
##   ..$ : num [1:5] 264 8.8 111 29 9.4
##   ..$ : num [1:5] 330 7.5 150 8.8 45
##   ..$ : num [1:4] 330 140 38 12
##   ..$ : num [1:5] 194 7.7 88.3 24.1 6.81
##   ..$ : num [1:5] 194 90.8 7.9 25 6.9
##   ..$ : num [1:2] 7.9 313
##   ..$ : num [1:4] 14 40 340 160
##   ..$ : num [1:5] 13 330 8 160 43
##   ..$ : num [1:2] 7.8 318
##   ..$ : num [1:5] 8.6 298 132 32.7 12.3
##   ..$ : num [1:5] 275 7.7 130 34 10
##   ..$ : num [1:5] 7.5 14 300 140 32
##   ..$ : num [1:5] 200 90 25 7.3 6.6
##   ..$ : num [1:2] 349 8.4
##   ..$ : num [1:2] 300 8.6
##   ..$ : num [1:5] 368 8.7 174 45 15
##   ..$ : num [1:5] 196 7.4 86 25 5.7
##   ..$ : num [1:5] 10 8 130 37 288
##   ..$ : num [1:5] 11 7.7 110 27 255
##   ..$ : num [1:5] 7.8 34 307 130 11
##   ..$ : num [1:5] 41 140 10 285 7.4
##   ..$ : num [1:2] 332 8.3
##   ..$ : num [1:5] 13 7.7 160 41 360
##   .. [list output truncated]
##  $ Nitrogen_mg.L               : num [1:774] NA NA NA NA 1.8 NA 0.65 0.69 NA NA ...
```

```
##  $ Temp_C                    : num [1:774] 25 20 25 16 23 24 24 23 13 28 ...
##  $ Phosphate_mg.L            : num [1:774] NA NA NA NA 1.2 NA 0.89 0.28 NA NA ...
##  $ Sediments_mg.L            : num [1:774] NA NA NA NA NA NA NA NA NA NA ...
```

```
# Create monthly summary dataset of water quality
ShenaWQ_monthly <- ShenaWQ_processed %>%
  group_by(Year, Month) %>%
  summarise(Sediment_min = min(Sediments_mg.L),
            Sediment_max = max(Sediments_mg.L),
            Sediment_mean = mean(Sediments_mg.L),
            Temp_min = min(Temp_C),
            Temp_max = max(Temp_C),
            Temp_mean = mean(Temp_C),
            Nitrogen_min = min(Nitrogen_mg.L),
            Nitrogen_max = max(Nitrogen_mg.L),
            Nitrogen_mean = mean(Nitrogen_mg.L),
            Phosphate_min = min(Phosphate_mg.L),
            Phosphate_max = max(Phosphate_mg.L),
            Phosphate_mean = mean(Phosphate_mg.L)) %>%
  mutate(Date = as.Date(paste(Year, Month, "1", sep = "-"), format = "%Y-%m-%d")) #%>%
```

```
## `summarise()` has grouped output by 'Year'. You can override using the `.groups` argu
```

```
  #unnest(Sediment_min:Phosphate_mean)

# Check dimensions and summary of dataset
dim(ShenaWQ_monthly)
```

```
## [1] 443  15
```

```
summary(ShenaWQ_monthly)
```

```
##       Year          Month         Sediment_min      Sediment_max
##  Min.   :1967   Min.   : 1.000   Min.   :  0.000   Min.   :   0.00
##  1st Qu.:1979   1st Qu.: 3.000   1st Qu.:  2.000   1st Qu.:   2.19
##  Median :2000   Median : 6.000   Median :  3.000   Median :   6.00
##  Mean   :1997   Mean   : 6.497   Mean   :  8.599   Mean   :  63.19
##  3rd Qu.:2012   3rd Qu.:10.000   3rd Qu.:  7.000   3rd Qu.:  51.00
##  Max.   :2022   Max.   :12.000   Max.   :282.000   Max.   :2020.00
##                                  NA's   :184       NA's   :184
##  Sediment_mean        Temp_min         Temp_max         Temp_mean
##  Min.   :  0.000   Min.   :-0.10   Min.   : 0.00   Min.   : 0.00
##  1st Qu.:  2.145   1st Qu.: 6.90   1st Qu.: 8.00   1st Qu.: 7.40
##  Median :  5.667   Median :13.80   Median :15.70   Median :14.95
##  Mean   : 32.953   Mean   :14.21   Mean   :15.79   Mean   :14.99
##  3rd Qu.: 34.750   3rd Qu.:22.50   3rd Qu.:23.40   3rd Qu.:23.00
##  Max.   :934.667   Max.   :30.20   Max.   :30.50   Max.   :30.20
```

```
##  NA's   :184       NA's   :6       NA's   :6       NA's   :6
##   Nitrogen_min     Nitrogen_max   Nitrogen_mean    Phosphate_min
##  Min.   :0.0100   Min.   :0.030   Min.   :0.0200   Min.   :0.000
##  1st Qu.:0.5925   1st Qu.:0.680   1st Qu.:0.6500   1st Qu.:0.021
##  Median :0.8750   Median :1.020   Median :0.9800   Median :0.123
##  Mean   :0.9018   Mean   :1.029   Mean   :0.9635   Mean   :0.217
##  3rd Qu.:1.2000   3rd Qu.:1.340   3rd Qu.:1.2994   3rd Qu.:0.313
##  Max.   :2.2000   Max.   :2.690   Max.   :2.3850   Max.   :1.930
##  NA's   :85       NA's   :85      NA's   :85       NA's   :94
##  Phosphate_max    Phosphate_mean         Date
##  Min.   :0.0000   Min.   :0.00000   Min.   :1967-10-01
##  1st Qu.:0.0430   1st Qu.:0.03467   1st Qu.:1979-03-17
##  Median :0.1690   Median :0.15000   Median :2000-11-01
##  Mean   :0.2636   Mean   :0.23902   Mean   :1997-05-22
##  3rd Qu.:0.4000   3rd Qu.:0.35000   3rd Qu.:2012-12-16
##  Max.   :1.9300   Max.   :1.93000   Max.   :2022-03-01
##  NA's   :94       NA's   :94
```

```
str(ShenaWQ_monthly)
```

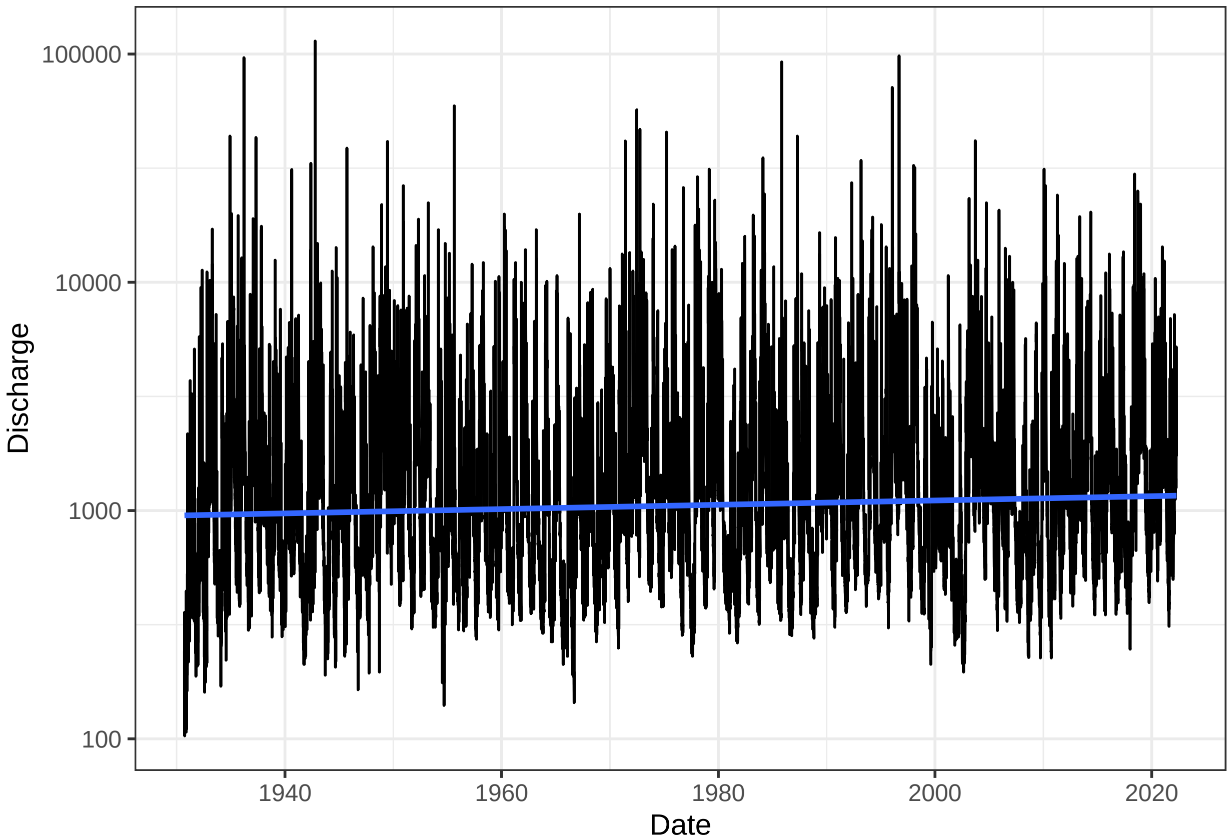
```
## grouped_df [443 x 15] (S3: grouped_df/tbl_df/tbl/data.frame)
##  $ Year          : num [1:443] 1967 1967 1967 1968 1968 ...
##  $ Month         : num [1:443] 10 11 12 1 2 3 4 5 11 12 ...
##  $ Sediment_min  : num [1:443] NA NA NA NA NA NA NA NA NA NA ...
##  $ Sediment_max  : num [1:443] NA NA NA NA NA NA NA NA NA NA ...
##  $ Sediment_mean : num [1:443] NA NA NA NA NA NA NA NA NA NA ...
##  $ Temp_min      : num [1:443] 9 8 4 0 3 6 15 23 6 2 ...
##  $ Temp_max      : num [1:443] 9 8 4 0 6 7 15 23 10 7 ...
##  $ Temp_mean     : num [1:443] 9 8 4 0 4.5 6.5 15 23 8 4.25 ...
##  $ Nitrogen_min  : num [1:443] NA NA NA NA NA NA NA NA NA NA ...
##  $ Nitrogen_max  : num [1:443] NA NA NA NA NA NA NA NA NA NA ...
##  $ Nitrogen_mean : num [1:443] NA NA NA NA NA NA NA NA NA NA ...
##  $ Phosphate_min : num [1:443] NA NA NA NA NA NA NA NA NA NA ...
##  $ Phosphate_max : num [1:443] NA NA NA NA NA NA NA NA NA NA ...
##  $ Phosphate_mean: num [1:443] NA NA NA NA NA NA NA NA NA NA ...
##  $ Date          : Date[1:443], format: "1967-10-01" "1967-11-01" ...
##  - attr(*, "groups")= tibble [46 x 2] (S3: tbl_df/tbl/data.frame)
##   ..$ Year : num [1:46] 1967 1968 1969 1970 1971 ...
##   ..$ .rows: list<int> [1:46]
##   .. ..$ : int [1:3] 1 2 3
##   .. ..$ : int [1:4] 4 5 6 7
##   .. ..$ : int [1:3] 8 9 10
##   .. ..$ : int [1:12] 11 12 13 14 15 16 17 18 19 20 ...
##   .. ..$ : int [1:12] 23 24 25 26 27 28 29 30 31 32 ...
##   .. ..$ : int [1:12] 35 36 37 38 39 40 41 42 43 44 ...
```

```
##    .. ..$ : int [1:12] 47 48 49 50 51 52 53 54 55 56 ...
##    .. ..$ : int [1:12] 59 60 61 62 63 64 65 66 67 68 ...
##    .. ..$ : int [1:12] 71 72 73 74 75 76 77 78 79 80 ...
##    .. ..$ : int [1:11] 83 84 85 86 87 88 89 90 91 92 ...
##    .. ..$ : int [1:11] 94 95 96 97 98 99 100 101 102 103 ...
##    .. ..$ : int [1:5] 105 106 107 108 109
##    .. ..$ : int [1:7] 110 111 112 113 114 115 116
##    .. ..$ : int [1:8] 117 118 119 120 121 122 123 124
##    .. ..$ : int [1:8] 125 126 127 128 129 130 131 132
##    .. ..$ : int [1:8] 133 134 135 136 137 138 139 140
##    .. ..$ : int [1:7] 141 142 143 144 145 146 147
##    .. ..$ : int [1:9] 148 149 150 151 152 153 154 155 156
##    .. ..$ : int [1:8] 157 158 159 160 161 162 163 164
##    .. ..$ : int [1:4] 165 166 167 168
##    .. ..$ : int 169
##    .. ..$ : int [1:6] 170 171 172 173 174 175
##    .. ..$ : int [1:12] 176 177 178 179 180 181 182 183 184 185 ...
##    .. ..$ : int [1:12] 188 189 190 191 192 193 194 195 196 197 ...
##    .. ..$ : int [1:12] 200 201 202 203 204 205 206 207 208 209 ...
##    .. ..$ : int [1:12] 212 213 214 215 216 217 218 219 220 221 ...
##    .. ..$ : int [1:12] 224 225 226 227 228 229 230 231 232 233 ...
##    .. ..$ : int [1:6] 236 237 238 239 240 241
##    .. ..$ : int [1:8] 242 243 244 245 246 247 248 249
##    .. ..$ : int [1:12] 250 251 252 253 254 255 256 257 258 259 ...
##    .. ..$ : int [1:12] 262 263 264 265 266 267 268 269 270 271 ...
##    .. ..$ : int [1:12] 274 275 276 277 278 279 280 281 282 283 ...
##    .. ..$ : int [1:12] 286 287 288 289 290 291 292 293 294 295 ...
##    .. ..$ : int [1:11] 298 299 300 301 302 303 304 305 306 307 ...
##    .. ..$ : int [1:12] 309 310 311 312 313 314 315 316 317 318 ...
##    .. ..$ : int [1:12] 321 322 323 324 325 326 327 328 329 330 ...
##    .. ..$ : int [1:12] 333 334 335 336 337 338 339 340 341 342 ...
##    .. ..$ : int [1:12] 345 346 347 348 349 350 351 352 353 354 ...
##    .. ..$ : int [1:12] 357 358 359 360 361 362 363 364 365 366 ...
##    .. ..$ : int [1:12] 369 370 371 372 373 374 375 376 377 378 ...
##    .. ..$ : int [1:12] 381 382 383 384 385 386 387 388 389 390 ...
##    .. ..$ : int [1:12] 393 394 395 396 397 398 399 400 401 402 ...
##    .. ..$ : int [1:12] 405 406 407 408 409 410 411 412 413 414 ...
##    .. ..$ : int [1:12] 417 418 419 420 421 422 423 424 425 426 ...
##    .. ..$ : int [1:12] 429 430 431 432 433 434 435 436 437 438 ...
##    .. ..$ : int [1:3] 441 442 443
##    .. ..@ ptype: int(0)
##    ..- attr(*, ".drop")= logi TRUE
```

3 Exploratory Analysis

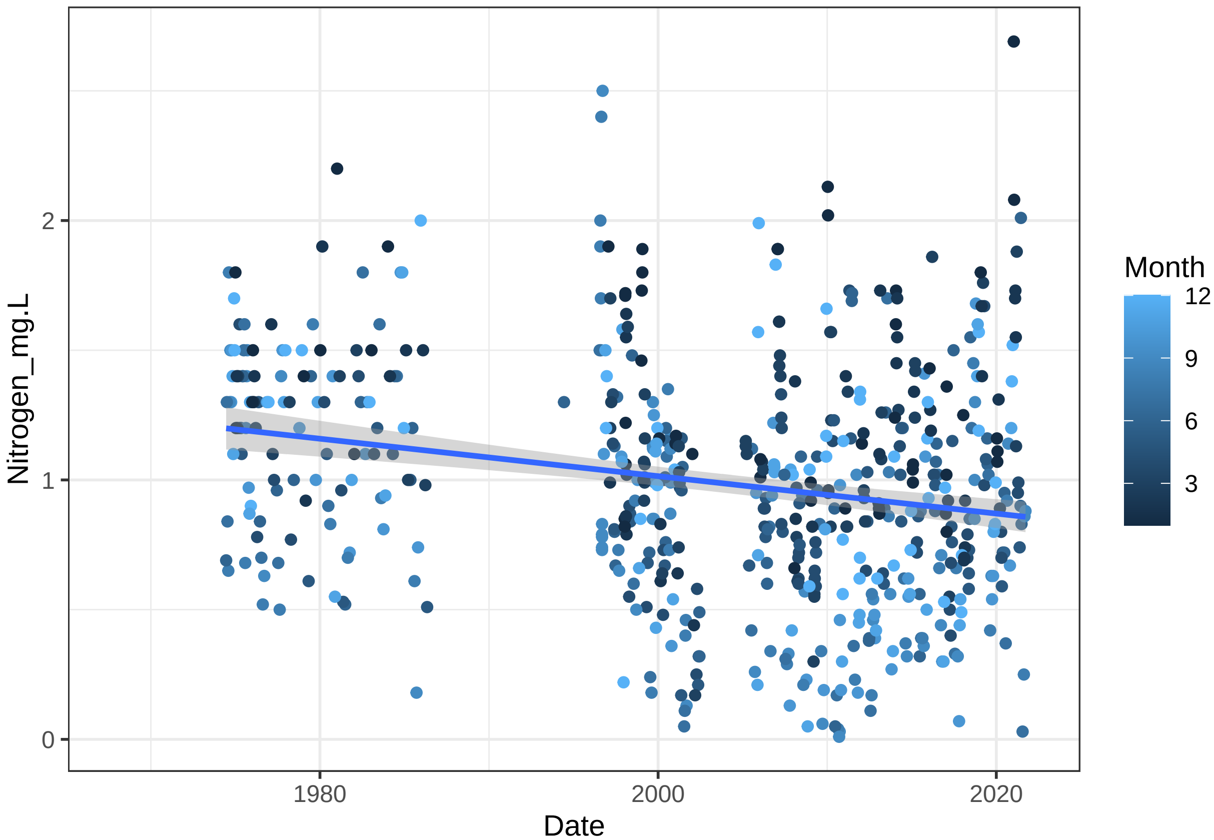
```
# View flow over time
ggplot(ShenaFlow, aes(x = Date, y = Discharge)) +
  geom_line() +
  geom_smooth(method = "lm") +
  scale_y_log10()
```

```
## `geom_smooth()` using formula 'y ~ x'
```




```
# View Nitrogen over time
# Elevated levels expected after dam removal but eventual decline
ggplot(ShenaWQ_processed, aes(x = Date, y = Nitrogen_mg.L)) +
  geom_point(aes(color = Month)) +
  geom_smooth(method = "lm")
```

```
## `geom_smooth()` using formula 'y ~ x'

## Warning: Removed 190 rows containing non-finite values (stat_smooth).

## Warning: Removed 190 rows containing missing values (geom_point).
```

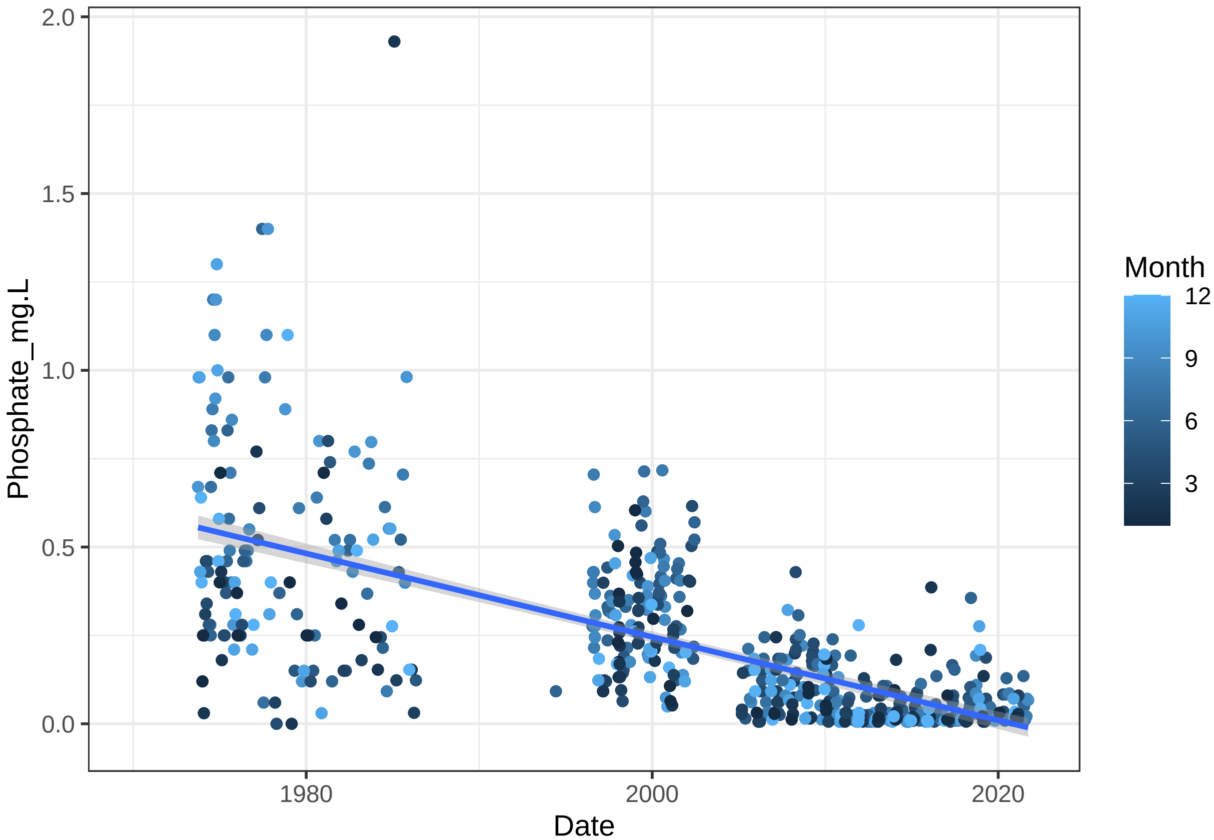



```r
# pull min, max, average

# View Phosphate over time
# Elevated levels expected after dam removal but eventual decline
ggplot(ShenaWQ_processed, aes(x = Date, y = Phosphate_mg.L)) +
  geom_point(aes(color = Month)) +
  geom_smooth(method = "lm") +
  scale_x_date(limits = c(as.Date("1970-01-01"),
                          as.Date("2022-02-17")))
```

```
## `geom_smooth()` using formula 'y ~ x'
```

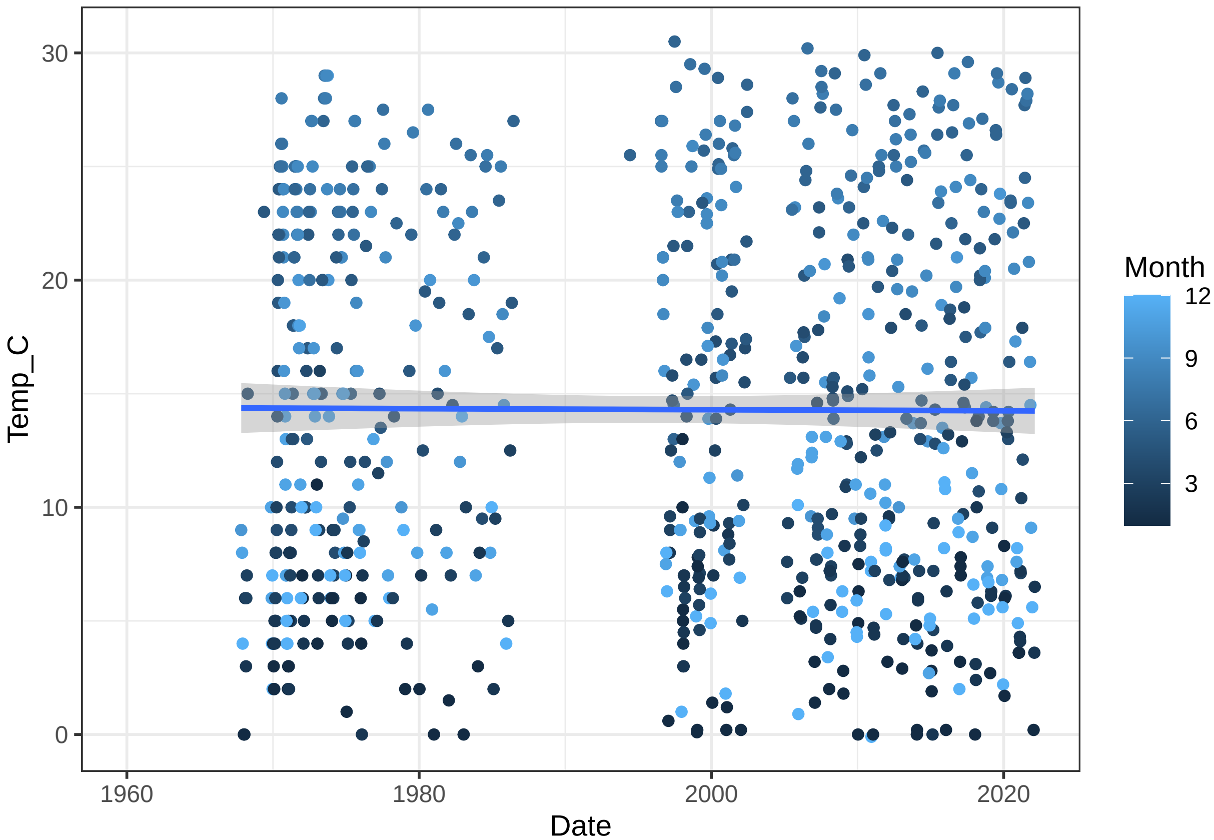
```
## Warning: Removed 195 rows containing non-finite values (stat_smooth).
```

```
## Warning: Removed 195 rows containing missing values (geom_point).
```




```r
# View Temp over time
ggplot(ShenaWQ_processed, aes(x = Date, y = Temp_C)) +
  geom_point(aes(color = Month)) +
  geom_smooth(method = "lm") +
  scale_x_date(limits = c(as.Date("1960-01-01"),
                          as.Date("2022-02-17")))
```

```
## `geom_smooth()` using formula 'y ~ x'

## Warning: Removed 8 rows containing non-finite values (stat_smooth).

## Warning: Removed 8 rows containing missing values (geom_point).
```

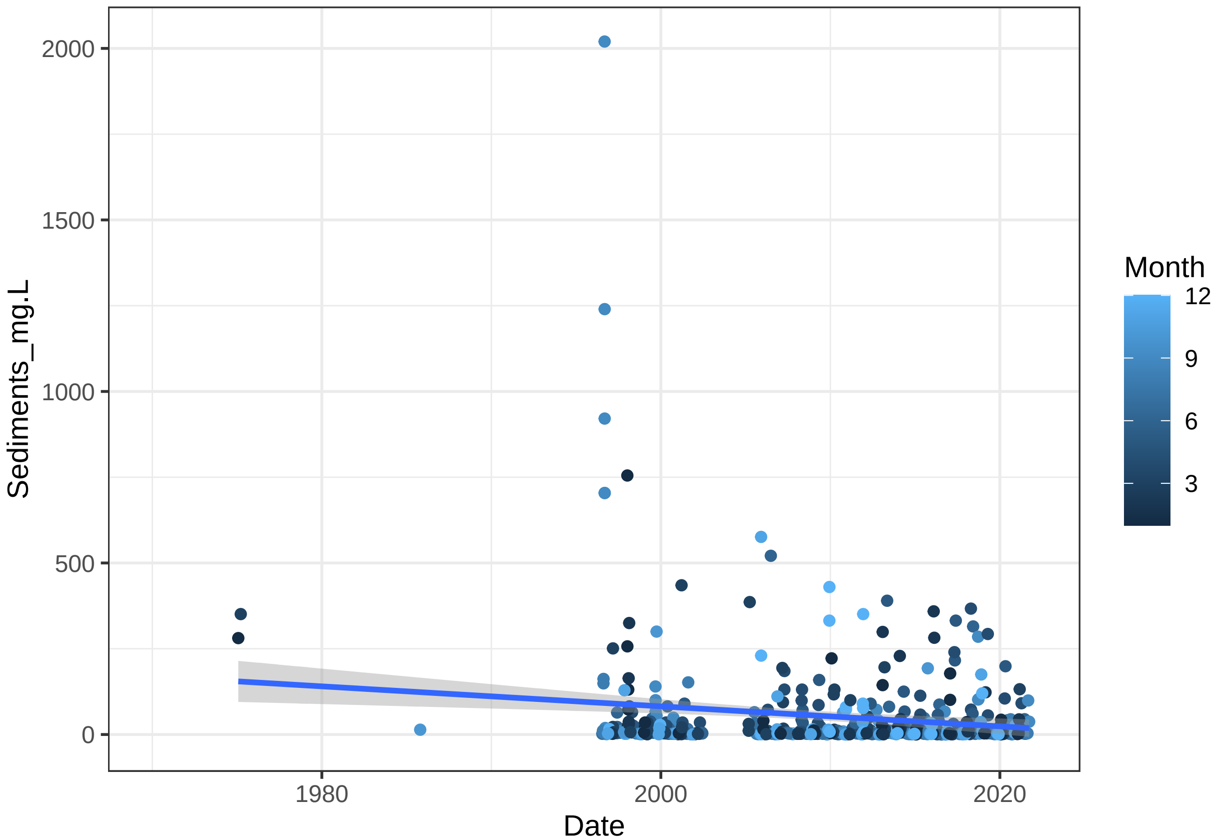



```r
# consider pulling average max min, and average per month

# View Sediments over time
# Predict increased sediment load right after dam removal, but eventual decline
ggplot(ShenaWQ_processed, aes(x = Date, y = Sediments_mg.L)) +
  geom_point(aes(color = Month)) +
  geom_smooth(method = "lm") +
  scale_x_date(limits = c(as.Date("1970-01-01"),
                          as.Date("2022-02-17")))
```

```
## `geom_smooth()` using formula 'y ~ x'
```

```
## Warning: Removed 308 rows containing non-finite values (stat_smooth).
```

```
## Warning: Removed 308 rows containing missing values (geom_point).
```

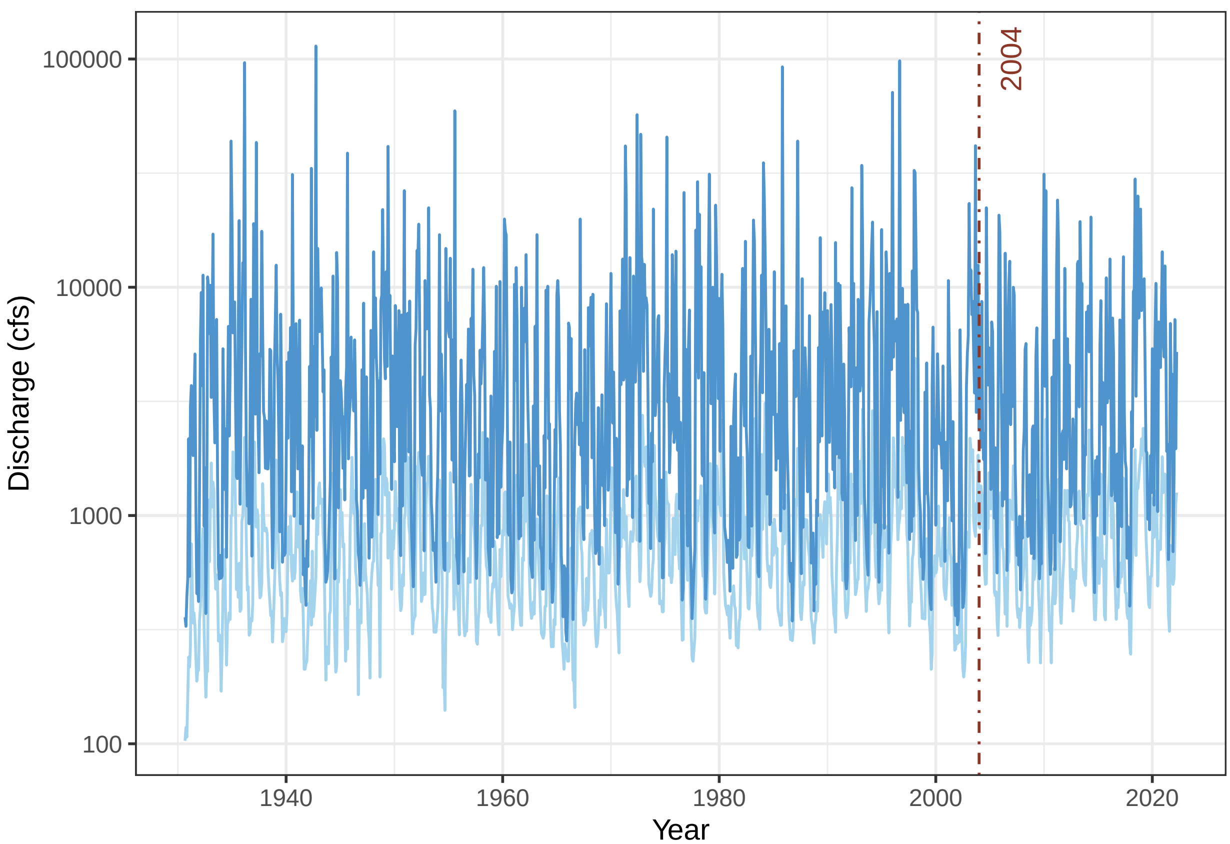



```
# TO DO
# Pick which analyses to run
# How to do quality analyses, given plentiful gaps in the data?
# Figure out how to do change point detection
```

4 Analysis

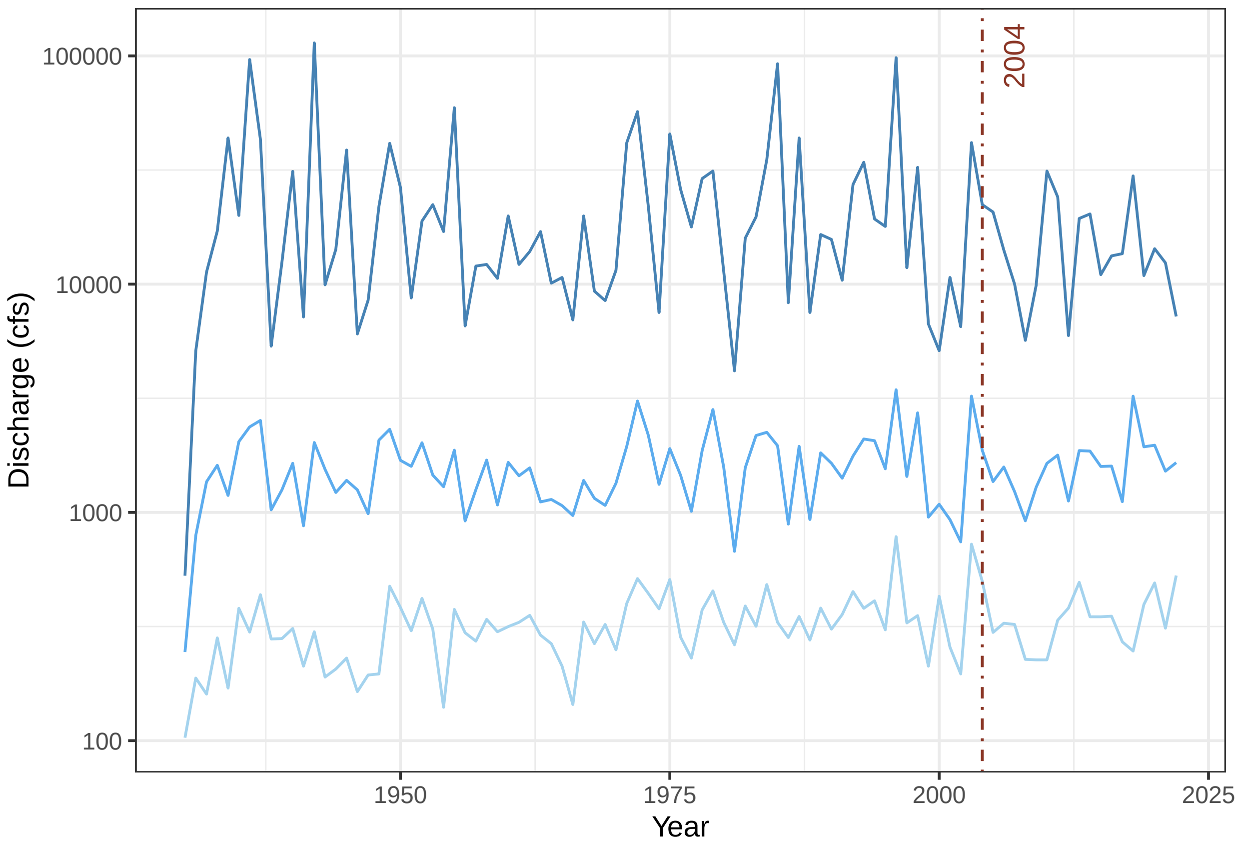
Question #1: Have discharge extremes increased since the removal of the dams? Has average discharge increased since dam removal?

```
# View monthly min and max flow over time
ggplot(ShenaFlow_monthly, aes(x = Date)) +
  scale_y_log10() +
  geom_line(aes(y = Discharge_min), color = "lightskyblue2") +
  geom_line(aes(y = Discharge_max), color = "steelblue3") +
  geom_vline(xintercept = as.numeric(as.Date("2004-01-01")),
             linetype = 4, color = "tomato4") +
  labs(x = "Year", y = "Discharge (cfs)") +
  annotate(geom = "text",
           label = "2004",
           x = as.Date("2004-01-01"),
           y = as.numeric(100000),
           angle = 90,
           vjust = 2,
           color = "tomato4")
```




```
# Extreme discharge does not appear to have increased. Check yearly to verify
```

```
# View yearly min, max, mean flow over time
ggplot(ShenaFlow_yearly, aes(x = Year)) +
  scale_y_log10() +
  geom_line(aes(y = Discharge_min), color = "lightskyblue2") +
  geom_line(aes(y = Discharge_max), color = "steelblue") +
  geom_line(aes(y = Discharge_mean), color = "steelblue2") +
  geom_vline(xintercept = as.numeric(2004),
             linetype = 4, color = "tomato4") +
  labs(y = "Discharge (cfs)") +
  annotate(geom = "text",
           label = "2004",
           x = as.numeric(2004),
           y = as.numeric(100000),
           angle = 90,
           vjust = 2,
           color = "tomato4")
```




```
# Yes, extremes appear smaller since the dam removal

# Create before and after datasets
ShenaFlow.before <- ShenaFlow[ShenaFlow$Date < "2004-01-01",]
ShenaFlow.after <- ShenaFlow[ShenaFlow$Date >= "2006-01-01",]
```

```r
# Create summary table to compare before and after dam removal
before_summary <- describe(ShenaFlow.before[,"Discharge"], fast = T)
after_summary <- describe(ShenaFlow.after[,"Discharge"], fast = T)
flow_summary <- rbind(before_summary, after_summary)
# rename columns
flow_summary$vars <- c("Before", "After")
colnames(flow_summary)[1] <- "Timeframe Relative to Dam Removal"

# Print summary table
kable(flow_summary, caption = "Summary Statistics for Discharge")
```

Table 1: Summary Statistics for Discharge

	Timeframe Relative to Dam Removal	n	mean	sd	min	max	range	
X1	Before	26764	1594.155	2687.319	103	114000	113897	16.42
X11	After	5950	1640.134	2010.450	226	31300	31074	26.06

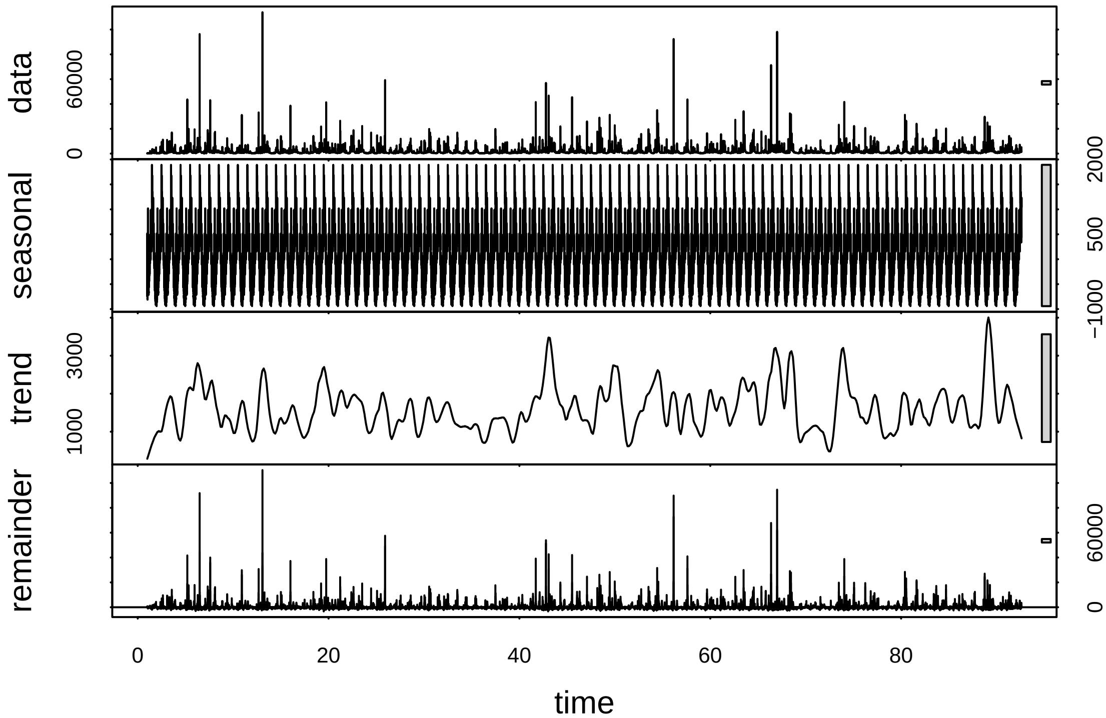
```r
# It appears that average flow may be higher since the dam removal
# Test with a t-test
t.test_before.after <- t.test(ShenaFlow.before$Discharge, ShenaFlow.after$Discharge, var
t.test_before.after
```

```
##
##  Welch Two Sample t-test
##
## data:  ShenaFlow.before$Discharge and ShenaFlow.after$Discharge
## t = -1.4925, df = 11220, p-value = 0.1356
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -106.36901   14.40966
## sample estimates:
## mean of x mean of y
##  1594.155  1640.134
```

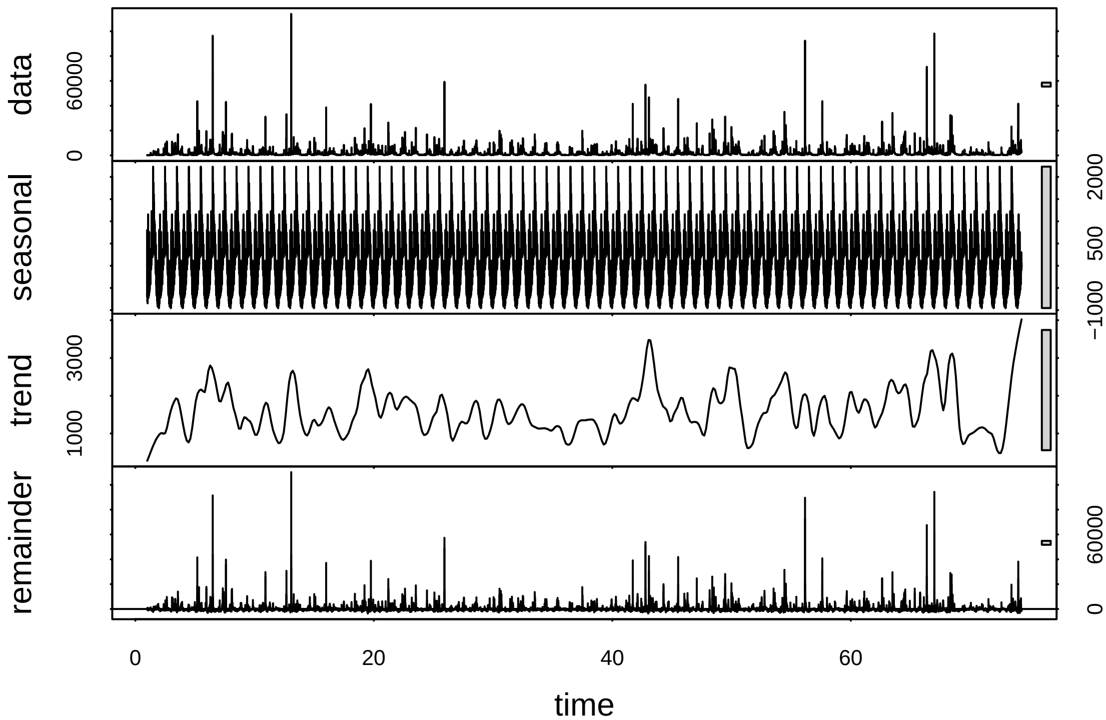
```r
# Not statistically different
```

```r
# FLOW TIME SERIES

Flow_ts <- ts(ShenaFlow[[4]], frequency = 365)

# Generate the decomposition
Flow_Decomposed <- stl(Flow_ts, s.window = "periodic")

# Visualize the decomposed series.
```

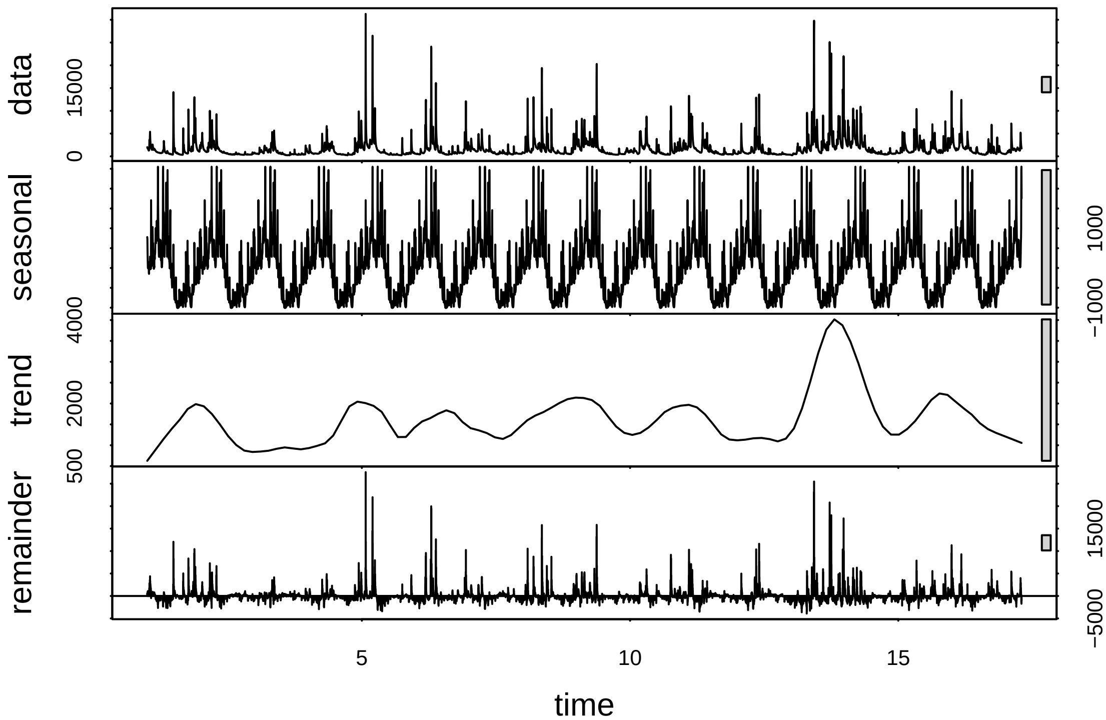
```
plot(Flow_Decomposed)
```



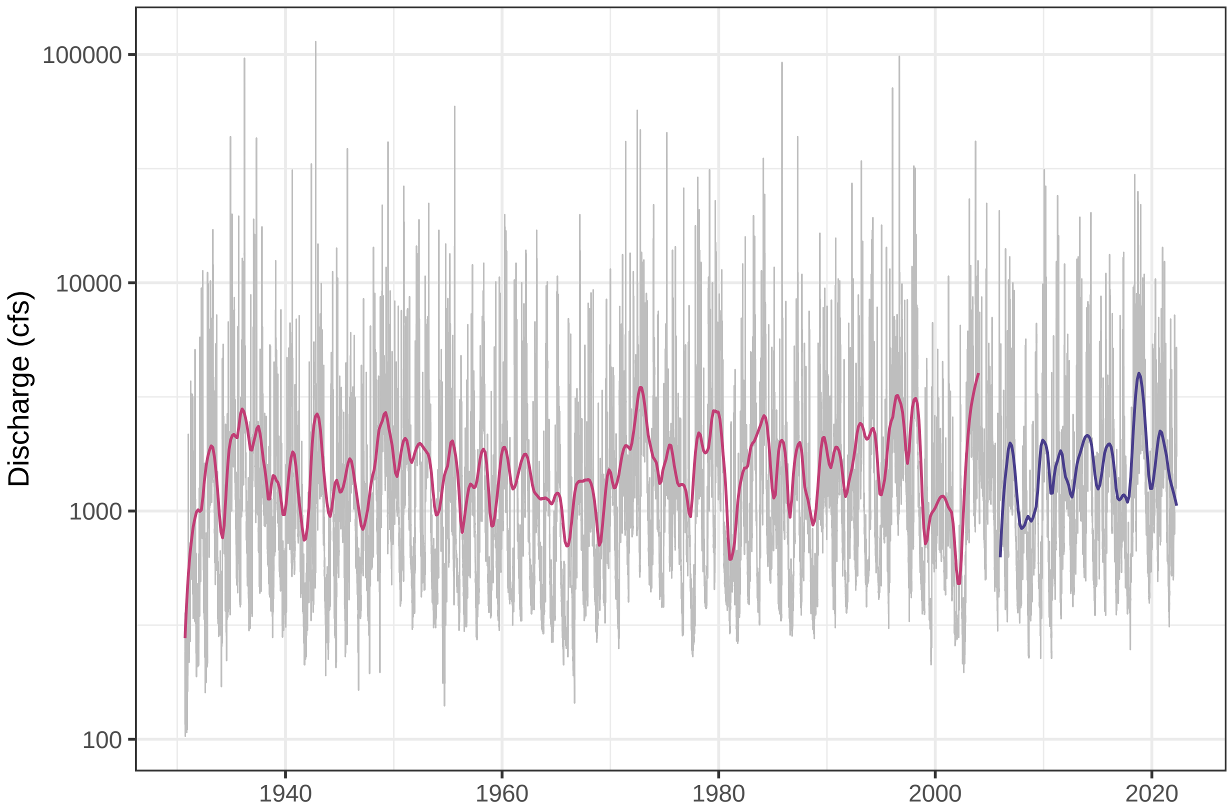

```
# Extract the components and turn them into data frames
Flow_Components <- as.data.frame(Flow_Decomposed$time.series[,1:3])
Flow_Components <- mutate(Flow_Components,
                          Observed = ShenaFlow$Discharge,
                          Date = ShenaFlow$Date)


# TIME SERIES BREAK DOWN BY BEFORE/AFTER DAM REMOVAL
# Flow Time Series: Before the Dam

Flow_ts.before <- ts(ShenaFlow.before[[4]], frequency = 365)

# Generate the decomposition
Flow_Decomposed.before <- stl(Flow_ts.before, s.window = "periodic")

# Visualize the decomposed series.
plot(Flow_Decomposed.before)
```




```
# Extract the components and turn them into data frames
Flow_Components.before <- as.data.frame(Flow_Decomposed.before$time.series[,1:3])
Flow_Components.before <- mutate(Flow_Components.before,
                      Observed = ShenaFlow.before$Discharge,
                      Date = ShenaFlow.before$Date)

# Repeat for after
# Flow Time Series: After the Dam

Flow_ts.after <- ts(ShenaFlow.after[[4]], frequency = 365)

# Generate the decomposition
Flow_Decomposed.after <- stl(Flow_ts.after, s.window = "periodic")

# Visualize the decomposed series.
plot(Flow_Decomposed.after)
```



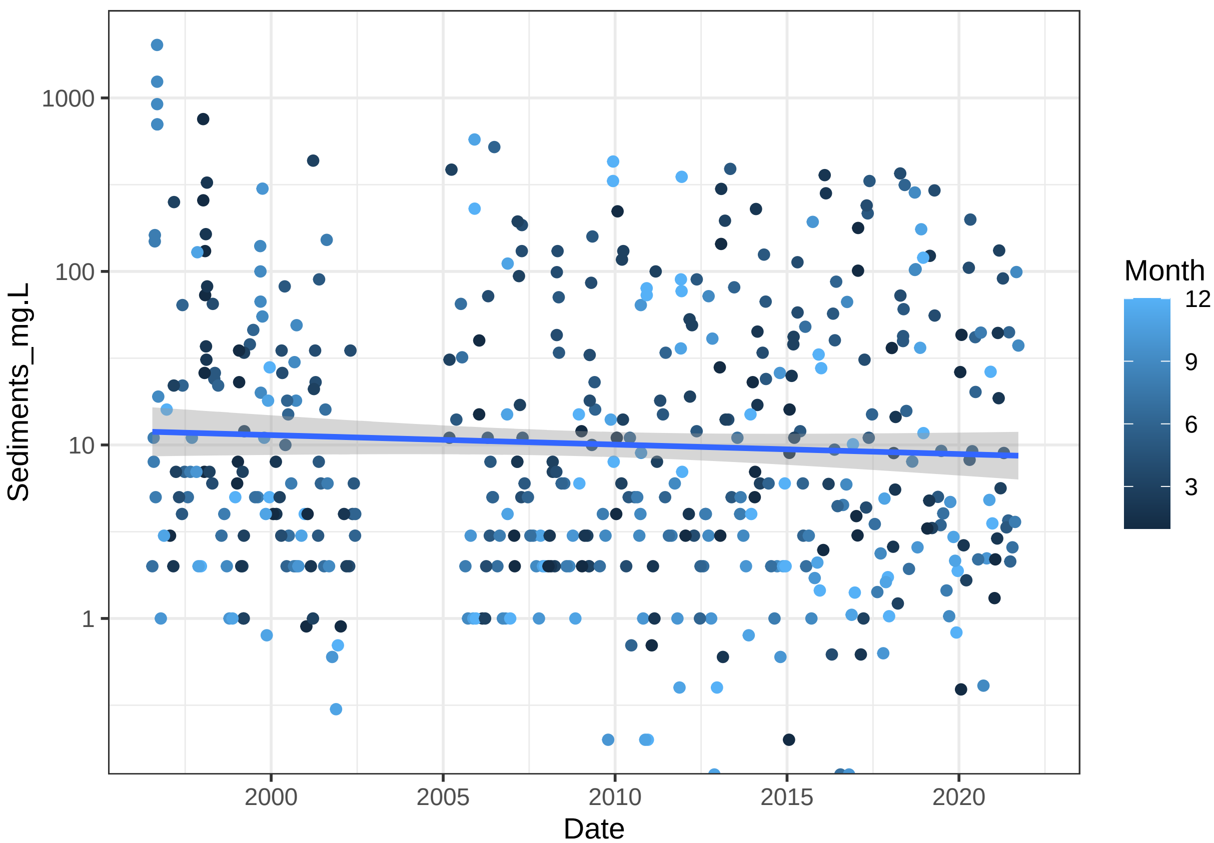

```
# Extract the components and turn them into data frames
Flow_Components.after <- as.data.frame(Flow_Decomposed.after$time.series[,1:3])
Flow_Components.after <- mutate(Flow_Components.after,
                        Observed = ShenaFlow.after$Discharge,
                        Date = ShenaFlow.after$Date)

# Graph before vs after trends
ggplot(Flow_Components) +
  geom_line(aes(y = Observed, x = Date), color = "gray", size = 0.25) +
  geom_line(data = Flow_Components.before, aes(y = trend, x = Date), color = "#c13d75ff"
  geom_line(data = Flow_Components.after, aes(y = trend, x = Date), color = "darkslatebl
  #geom_hline(yintercept = 0, lty = 2) +
  labs(x = "", y = "Discharge (cfs)") +
  scale_y_log10()
```


Discharge (cfs)
100000
10000
1000
100
1940
1960
1980
2000
2020

Question #2: Has there been an increase in release of sediment and nutrients over time? #+ Have levels increased since dam removal, or did they spike and then stabilize?

```
# Re-examine data, excluding small number of early points and rescaling
ggplot(data = ShenaWQ_processed[ShenaWQ_processed$Date > "1995-01-01",],
             aes(x = Date, y = Sediments_mg.L, color = Month)) +
  geom_point() +
  geom_smooth(method = "lm") +
  scale_y_log10()
```

```
## Warning: Transformation introduced infinite values in continuous y-axis

## Warning: Transformation introduced infinite values in continuous y-axis

## `geom_smooth()` using formula 'y ~ x'

## Warning: Removed 21 rows containing non-finite values (stat_smooth).

## Warning: Removed 18 rows containing missing values (geom_point).
```




```
# Sediment levels have clearly not increased over time!

# Create before and after WQ datasets
ShenaWQ.before <- ShenaWQ_processed[ShenaWQ_processed$Date < "2004-01-01",]
```

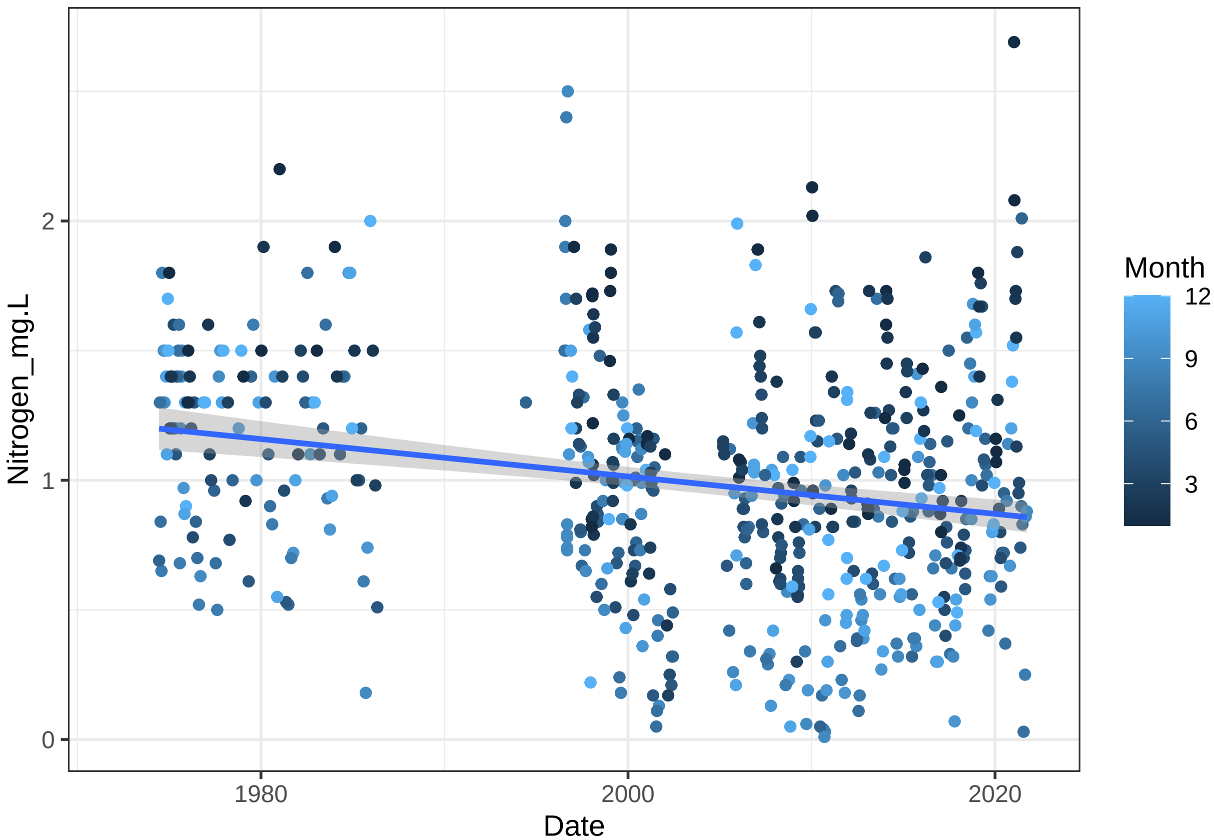
```r
ShenaWQ.after <- ShenaWQ_processed[ShenaWQ_processed$Date >= "2006-01-01",]

# Test whether average sediment varied before versus after dam removal
t.test_sediment <- t.test(ShenaWQ.before$Sediments_mg.L, ShenaWQ.after$Sediments_mg.L, v
t.test_sediment
```

```
##
##  Welch Two Sample t-test
##
## data:  ShenaWQ.before$Sediments_mg.L and ShenaWQ.after$Sediments_mg.L
## t = 1.9798, df = 148.99, p-value = 0.04957
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##   0.08085757 84.02230236
## sample estimates:
## mean of x mean of y
##  83.15474  41.10316
```

```r
# Sediment levels were significantly lower post (p = 0.050)
# Not possible to see whether there was a spike immediately after dam
# removal because of gap in data
```

```r
# Re-examine data, zoomed in
ggplot(ShenaWQ_processed, aes(x = Date, y = Nitrogen_mg.L)) +
  geom_point(aes(color = Month)) +
  geom_smooth(method = "lm") +
  scale_x_date(limits = c(as.Date("1972-01-01"),
                          as.Date("2022-02-17")))
```

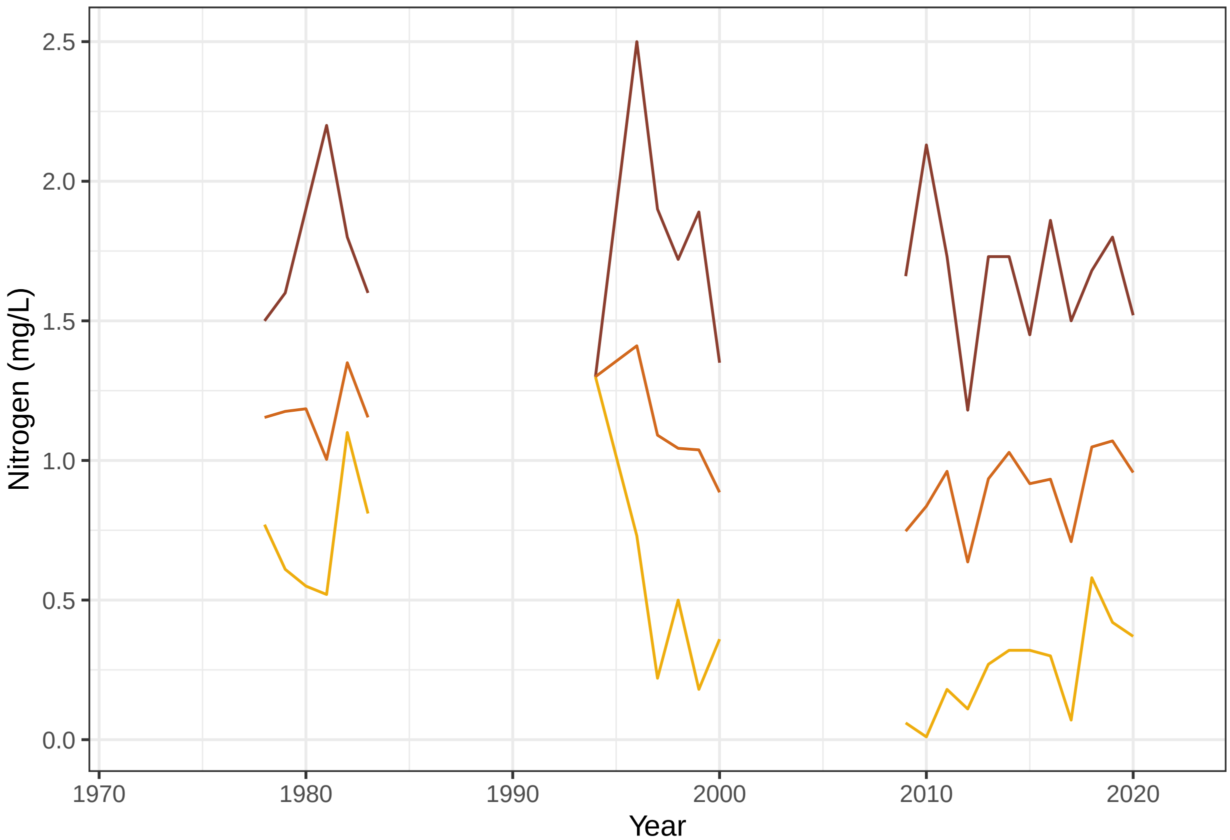
```
## `geom_smooth()` using formula 'y ~ x'

## Warning: Removed 190 rows containing non-finite values (stat_smooth).

## Warning: Removed 190 rows containing missing values (geom_point).
```




```r
# Sediment levels have clearly not increased over time!

# Create yearly summary table to visualize differently
ShenaWQ_yearly <- ShenaWQ_processed %>%
  group_by(Year) %>%
  summarise(Nitrogen_min = min(Nitrogen_mg.L),
            Nitrogen_max = max(Nitrogen_mg.L),
            Nitrogen_mean = mean(Nitrogen_mg.L)) %>%
  filter(Year >= 1972)

# Plot results
```

```r
ggplot(ShenaWQ_yearly, aes(x = Year)) +
  geom_line(aes(y = Nitrogen_min), color = "darkgoldenrod2") +
  geom_line(aes(y = Nitrogen_max), color = "coral4") +
  geom_line(aes(y = Nitrogen_mean), color = "chocolate") +
  labs(y = "Nitrogen (mg/L)")
```

```
## Warning: Removed 6 row(s) containing missing values (geom_path).

## Warning: Removed 6 row(s) containing missing values (geom_path).

## Warning: Removed 6 row(s) containing missing values (geom_path).
```




```r
# Test whether average sediment varied before versus after dam removal
t.test_nitrogen <- t.test(ShenaWQ.before$Nitrogen_mg.L, ShenaWQ.after$Nitrogen_mg.L, var
t.test_nitrogen
```

```
##
##  Welch Two Sample t-test
##
## data:  ShenaWQ.before$Nitrogen_mg.L and ShenaWQ.after$Nitrogen_mg.L
## t = 4.5603, df = 550.8, p-value = 0.000006299
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
```

```
##  0.0961950 0.2417647
## sample estimates:
## mean of x mean of y
## 1.0861811 0.9172013
```

```
# Sediment levels were significantly lower post (p < 0.001)
# Not possible to see whether there was a spike immediately after dam
# removal because of gap in data
```

5 Summary and Conclusions

6 References

- Foley, M. M., J. R. Bellmore, J. E. O'Connor, J. J. Duda, A. E. East, G. E. Grant, C. W. Anderson, J. A. Bountry, M. J. Collins, P. J. Connolly, L. S. Craig, J. E. Evans, S. L. Greene,F. J. Magilligan, C. S. Magirl, J. J. Major, G. R. Pess,T. J. Randle, P. B. Shafroth, C. E. Torgersen, D. Tullos, A. C. Wilcox. 2017. Dam removal: Listening in. Water Resources Research. 53(7):5229-5246. https://doi-org.proxy.lib.duke.edu/10.1002/2017WR020457

Map source: http://www.virginiaplaces.org/watersheds/fishpassage.html

Sediment deposits alter downstream tidal communities https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0187742#references