

A Suite of Tools for Analyzing Hydrology and Geomorphology in Impounded Rivers

An Honors Paper for the Department of Earth and Oceanographic Science

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“An unspoiled river is a very rare thing in this Nation today. Their flow and vitality have been harnessed by dams and too often they have been turned into open sewers by communities and by industries. It makes us all very fearful that all rivers will go this way unless somebody acts now to try to balance our river development.” – President Lyndon B. Johnson, October 2, 1968

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Abstract

Large impoundment dams have well-documented impacts on hydrologic and geomorphic function. Numerous tools and metrics have been developed over time to characterize these impacts, but they remain disparate, are often applied in a small number of studies, and rarely applied in concert with each other. Utilizing the open-source programming language R, I assemble a suite of metrics known as DAMS – the Dam Analysis and Metrics Suite – that combines several pre-existing metrics for characterizing dam impacts into one script. These metrics include the Indicators of Hydrologic Alteration to characterize hydrologic change; the mean streambed elevation to characterize vertical change in the river; and sediment mass balance and flood magnitude reduction. By combining these schemas, DAMS provides a flexible and comprehensive way to characterize the impact of dams on hydrology and geomorphology.

I apply DAMS to two dams in diverse geographic settings: the Buford Dam on the Chattahoochee River in Georgia and the Harris Station Dam on the Kennebec River in Maine. Both are hydroelectric dams with long stream gage records before and after dam construction. I found that the Buford Dam has caused a decrease in high flows in the Chattahoochee River as well as a change in the seasonality of flows. I found that the Kennebec River has seen an increase in high and peak flow volume after the construction of the Harris Station Dam, but this increase is less than comparable unimpounded rivers. The geomorphic data the Chattahoochee River is fairly limited and cannot be access for the Kennebec River at all, meaning that DAMS was unable to tell a complete story about how these rivers changed due to impoundment, highlighting the need for increased monitoring on all of the United States' rivers.

1. Introduction

The rivers of the United States are covered in dams. As of 2013, the United States had 6,433 dams over 50 feet in height (Mulligan et al., 2020). Today, there are more than 90,000 dams in the United States of all sizes (*National Inventory of Dams*, n.d.). We have built dams from sea to shining sea. We have built dams on rivers big and small. While the exact reason for this control ranges from hydropower to obtaining water for population centers to agriculture to economic stimulus from construction or a combination of these or other reasons, we found ways to stop water from flowing where and when it naturally would otherwise.

For most of the 20th century, America was in a dam building craze. This era of American dam building began in earnest in 1935 with the dedication and subsequent opening of the Hoover Dam on the Colorado River. During this era, we built large impoundments on countless American rivers. The construction of these large dams allowed for the agricultural, economic, and population boom in the 20th century (Di Baldassarre et al., 2021). However, in the last 40 years, the United States has virtually stopped constructing dams (Lee, 2023). Nevertheless, there is a large dam under construction in California that is nearing completion that will create a reservoir to increase water storage in preparation for drought periods. It is the first large dam project in the United States in decades (Randle & Linville, 2024)

One major reason for the decline in the impounding of American rivers was due to a growing environmental movement and lobby in the 1970s. Despite the positive impacts dams had on American growth, this was often at the expense of the health of rivers. People began to understand that dams were changing the rivers they lay on, often to the detriment of the rivers and environment at large.

In the last 40 years, the scientific community has created methods to quantify how a river has changed over time due to impoundment. There are various metrics that can be implemented to gain an understanding of how the flow regime of a river, or the physical characteristics of the river has changed. While each individual metric or method of measuring change does not tell the complete story of how a singular river has changed, it is part of the story of the alteration of the river. A complete story of the river can be told when metrics are measured together and placed in context with the physical characteristics of the river and watershed.

1.2 Literature Review

In 1984, Williams and Wolman published “Downstream Effects of Dams on Alluvial Rivers.” This report examined how downstream geomorphology and hydrology were altered by the impoundment of rivers. It was one of the first papers in a growing body of work dedicated to understanding and quantifying the effects that dams have rivers they impound. Williams and Wolman measured changes in water discharge, sediment load, bed and bank materials, mean bed elevation, channel width, and channel vegetation growth. By examining 21 dammed rivers throughout the American west, Midwest, and southeast, they concluded that dams greatly alter the timing and quantity of streamflow and the downstream physical environment (Williams & Wolman, 1984). They reported that dams cause large magnitude of geomorphic change, but geomorphic change is not predictable and based on watershed characteristics and dam operations (Williams & Wolman, 1984). Hydrologic change was more predictable with high flows decreasing downstream of the dam for nearly every river, dependent of dam release schedule and operations. (Williams & Wolman, 1984). In addition, they found that sediment supply

greatly decreased as much of the sediment was trapped in the impoundment (Williams & Wolman, 1984). This study gave insight into the drastic changes that impoundment had on rivers.

In the ensuing years, papers have been published that contain metrics that measure change in riverine hydrology or geomorphology. Some examine the influence that dams have on rivers (Blythe & Schmidt, 2018; Grant et al., 2003; Magilligan et al., 2003; Magilligan & Nislow, 2005; Richter et al., 1996a; Schmidt & Wilcock, 2008a; White et al., 2005) while others are more general descriptors of alteration in rivers and are not explicitly meant to assess the impacts of impoundment (Slater et al., 2015; Smelser & Schmidt, 1998). Each of these studies have added to the understanding of how to measure the change in rivers over time.

The Indicators of Hydrologic Alteration (IHA) measure hydrologic change in a river based on changes in flow magnitude, timing, duration, frequency, and rate of change. The IHA contains 33 metrics divided into five groups (Richter et al., 1996). This series of metrics has been important to dam and river science over the past 30 years. For many years, the IHA was accessible to those without knowledge of how to calculate each metric or without coding skills. The Nature Conservancy created a program that allowed users to apply all the metrics of the IHA quickly with minimal user input (The Nature Conservancy, 2009). This program was used in scientific research, education, and environmental advocacy and non-profit work (The Nature Conservancy, n.d.). However, the program does not run on modern operating systems. Additionally, there is an R package titled “IHA” (Law, 2016). While useful for calculating the metrics from raw data, it requires knowledge of R to use, and its outputs are limited to the metrics and not graphical or statistical analysis. This means that while the IHA is still an

important group of metrics, it is no longer as accessible for those without a background in coding or the calculation of each metric.

Numerous studies that have attempted to quantify hydrologic change of a river, due to impoundment or otherwise, have used the IHA (e.g. Cheng et al., 2018; Graf, 2006; Han et al., 2020; Magilligan & Nislow, 2005; Maingi & Marsh, 2002; Pyron & Neumann, 2008; Shieh et al., 2007; Timpe & Kaplan, 2017). Most of these papers focus only on one watershed or region, but Magilligan and Nislow (2005) and Graf (2006) focus large dams throughout the United States in a similar style as Williams and Wolman (1984).

Magilligan and Nislow (2005) applied the IHA to 21 river reaches downstream of dams with USGS stream gages with 30 years of record before and after dam construction, an original condition for the use of the IHA in Richter et al. (1996). They then ran a stepwise regression across all gage locations to determine what dam characteristics and climatic conditions attributed to change in each IHA metric. Magilligan and Nislow found that 1-day peak flows decrease and as the length of the time of the peak flow increases, the effect of impoundment decreases; low flows generally increase but less consistently than high flows decreasing; and generally spring flow decreases and later summer and fall flow increases (2005). In addition, Magilligan and Nislow represent IHA metrics that measure the timing of flows so flows at the very start and end of the calendar year are similar statistically and graphically rather than complete opposite (2005). This means the implementation of vectors to represent days of the year and plotting their results on circular diagrams.

In 2006, Graf implemented geomorphic metrics in addition to IHA to measure change in rivers downstream of dams due to impoundment. In this study, Graf studied a selection of 36 of America's largest dams with reservoirs greater than 1.2 km³ of storage that are greater than 30 years old. Graf measured hydrologic change using a selection of metrics from the IHA, and geomorphic change was measured using change in "low flow channels high flow channels, low bars, high bars, islands, active flood plains, and some engineered surfaces" (Graf, 2006). The hydrologic results generally align with the findings in Williams and Wolman (1984). The geomorphic results show that downstream of dams, the active channel generally shrinks and is simpler when compared with non-impounded counterparts.

Schmidt and Wilcock implemented Lane's balance (1) – a proportion between rate of sediment supply, grain size, water discharge, and channel slope needed to transport sediment – to help understand changes in sediment mass balance (2008). They presented a metric (2) that calculated the change in slope from pre-dam to post-dam needed to transport the sediment in the stream channel (Schmidt & Wilcock, 2008). When $S^{**} > 1$, the slope of the river in post-dam conditions is less than the necessary slope to transport post-dam sediment supply, indicating a sediment surplus and potential streambed aggradation. When $S^{**} < 1$, the slope of the river in post-dam conditions is greater than the necessary slope to transport post-dam sediment supply, indicating a sediment deficient and potential streambed degradation (Schmidt & Wilcock, 2008). This metric assumes channel width is constant from pre-dam to post-dam conditions.

<div style="text-align: right; margin-bottom: 10px;">Lane's Balance: $Qs * D \propto Q * S$ (1)</div> <div style="text-align: center; margin-bottom: 10px;"> $S^* = \frac{S_{post}}{S_{pre}} \quad Qs^* = \frac{Qs_{post}}{Qs_{pre}} \quad Q^* = \frac{Q_{post}}{Q_{pre}} \quad D^* = \frac{D_{post}}{D_{pre}}$ </div> <div style="text-align: right; margin-bottom: 10px;">Sediment Mass Balance Proxy: $S^{**} = \frac{(Qs^*)^{0.5} * (D^*)^{0.75}}{Q^*}$ (2)</div> <div style="text-align: center;"> <p>where</p> <ul style="list-style-type: none"> - Qs is the rate of sediment supply, - D is the grain size of sediment supply, - Q is water discharge, - S is the channel slope needed to transport sediment </div>
--

Schmidt and Wilcock also present a flood reduction metric to understand changes in flooding due to the construction of dams (2008). Flood reduction is reported as Q^* and is the ratio between the 2-year flood recurrence interval post-dam and pre-dam. $Q^* > 1$ indicated an increase in flood magnitude while $Q^* < 1$ indicated a decrease in flood magnitude (Schmidt & Wilcock, 2008).

Additional papers have presented metrics that measure changes in a river. These metrics are not specific to impounded rivers but can be applied to rivers with dams to provide information about geomorphic changes over time. Mean stream bed elevation (MSBE) is mean elevation of the entire stream bed at a given cross section (Smelser & Schmidt, 1998). Stream width and stream capacity (cross sectional area) at any given cross section can also be used to measure change in rivers (Slater et al., 2015).

1.3 The Knowledge Gap

Despite the body of work studying the effects dams have on rivers and the creation of metrics, there is more information is needed about the long term affects large dams have on rivers. The effects of impoundment on some rivers have never been studied or not studied in decades. Additionally, Large hydropower dams have been built on every

continent besides Antarctica. Most of the world's longest rivers are dammed. 63% of rivers over 1,000 km in length are impounded in some manner at some point on the way to the ocean (Grill et al., 2019).

The age of dams is not evenly distributed throughout the world. Generally, dams in the global north are older than their counterparts in the global south. There have been relatively few dams built in North America, Europe, and Oceania since 1990, while around 30% of dams in Africa and Asia have been built since then, and around 50% of dams in South America have been built since 1990 (Fig. 1) (Zhang & Gu, 2023). The study of older dams can provide insight into the lifecycle of dam impacts, which can be used to forecast the impact of younger dams in the global south. This could be done in a multitude of ways, from studies that examine a multitude of new and old dams to a study that compares two comparable dams in similar settings, one new and one

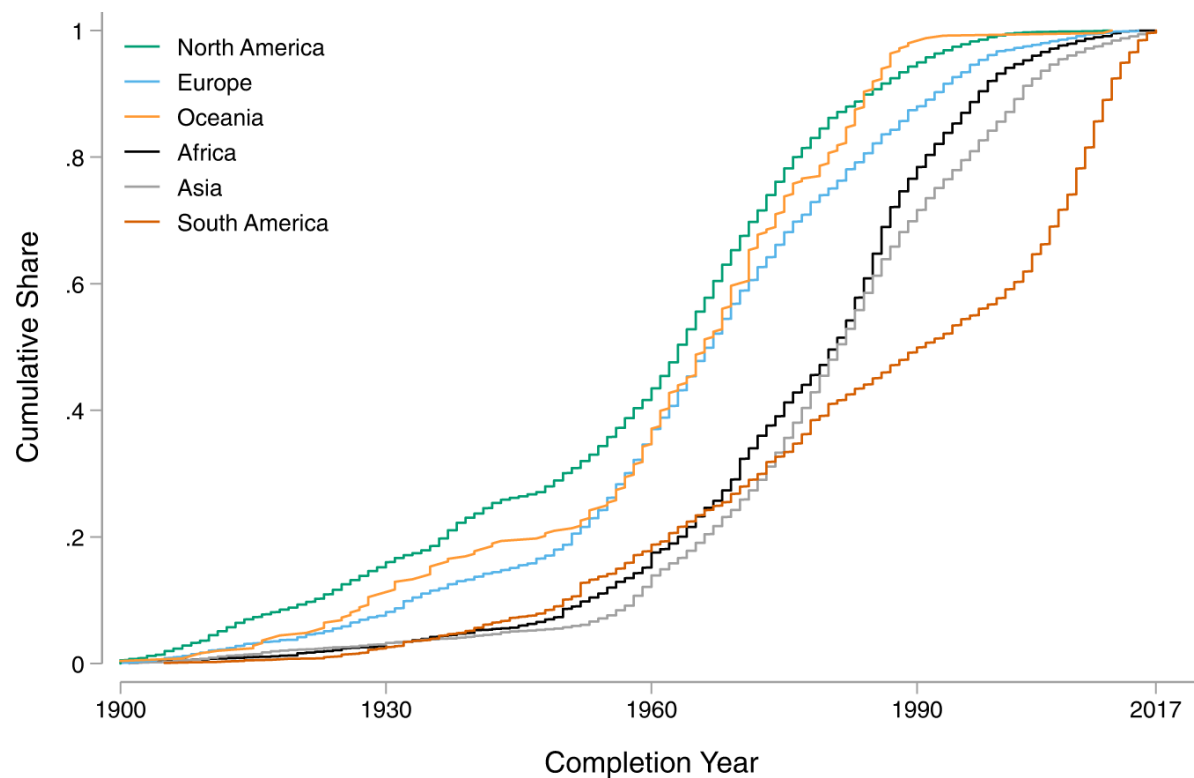


Figure 1. Distribution of dam completion year by continent. From Zhang and Gu, 2023

old. The alteration the older dam caused to its river could be mapped onto the river with the newer dam, helping predict future change.

1.4 Goals

Currently, we do not have a tool that easily calculates metrics that measure change in riverine geomorphology and hydrology downstream of dams, let alone one that provides relevant statistical and graphical analysis alongside the metrics. Additionally, despite the body of work that has been published that quantifies downstream geomorphic and hydrologic change due to dams, metrics are rarely used together. This means it is more difficult to assess the total alteration a dam has on the geomorphology and hydrology of a river. There are multiple papers that apply different metrics to impounded rivers (Graf, 2006; Magilligan & Nislow, 2005; Schmidt & Wilcock, 2008; Williams & Wolman, 1984). While they all employ some of the same metrics, there is also inconsistency in which metrics are applied and over which rivers.

DAMS – the Dam Analysis and Metric Suite – is a tool that can solve each of these problems. The DAMS R script calculates a suite of metrics that allows end users to supply minimal inputs and easily determine metrics from various papers (Richter et al., 1996; Schmidt & Wilcock, 2008; Slater et al., 2015; Smelser & Schmidt, 1998) as well as other commonly used hydrologic and geomorphic metrics. DAMS provides graphs to visualize change and statistical analyses to measure the amount and significance of said change. DAMS is designed to be modular, meaning that adding metrics will not be

difficult. In the over 40 years since Williams and Wolman (1984) was published, the climate has changed, populations and demographics have shifted, and dams have gotten older. DAMS can facilitate a study of a large number of dams and how they have altered the rivers they impound. The use case for DAMS extends beyond impounded rivers to any gaged river. The easy of use of DAMS means that it can be used in a wide range of environments, including academia, education, and in environmental activism and remediation, much like The Nature Conservancy program of years past.

As a proof of concept, DAMS was applied to two rivers with distinct hydrologic and sociodemographic regimes – the Buford Dam on the Chattahoochee River, GA and the Harris Station Dam on the Kennebec River, ME. The Buford Dam was chosen because it was one of the dams studied in Williams and Wolman (1984), Magilligan and Nislow (2005), and Graf (2006). The Buford Dam and the affects it has on the Chattahoochee River have been well studied, but the last 20 years of change have not been considered. The Harris Station Dam was chosen because it is a relatively unstudied dam. The effects the Harris Station Dam has had on the Kennebec River have not been published.

2. Methods

2.1 Overview of DAMS

DAMS is written in the open-source statistical programming language R. DAMS accesses stream gage data the United States Geological Survey (USGS) National Water Information System (NWIS) and uses this data to calculate metrics. The outputs of DAMS are tables of calculated metrics, and graphs for each metric and statistical analysis.

2.2 DAMS Inputs

The first step in DAMS is inputting the necessary information (Fig. 2). For DAMS to be applied to a river, there must be a USGS stream gage on the reach of the river to be studied. If there is one, it can be found on the USGS NWIS web interface at <https://waterdata.usgs.gov/nwis/rt> (U.S. Geological Survey, 2001). The DAMS user then must input the eight-digit USGS code for that stream gage into DAMS. In addition, the user must decide on the date ranges they wish to compare, and the time breaks for the end of the first and second time periods. DAMS allows for the comparison of three different time periods. All three time periods must be used, and each time period must be consecutive with no time gaps. However, one of the three time periods can be set to the length of zero days, effectively allowing the user to compare only two time periods. This could be a pre-dam to post-dam change or change the first 20 years after dam construction to the next 20 years after dam construction. The user inputs the start of date range, end of the first time period, end of the second time period, and the final time period all in YYYY-MM-DD format. The user can also input the name of the stream gage, an optional input, for record keeping purposes

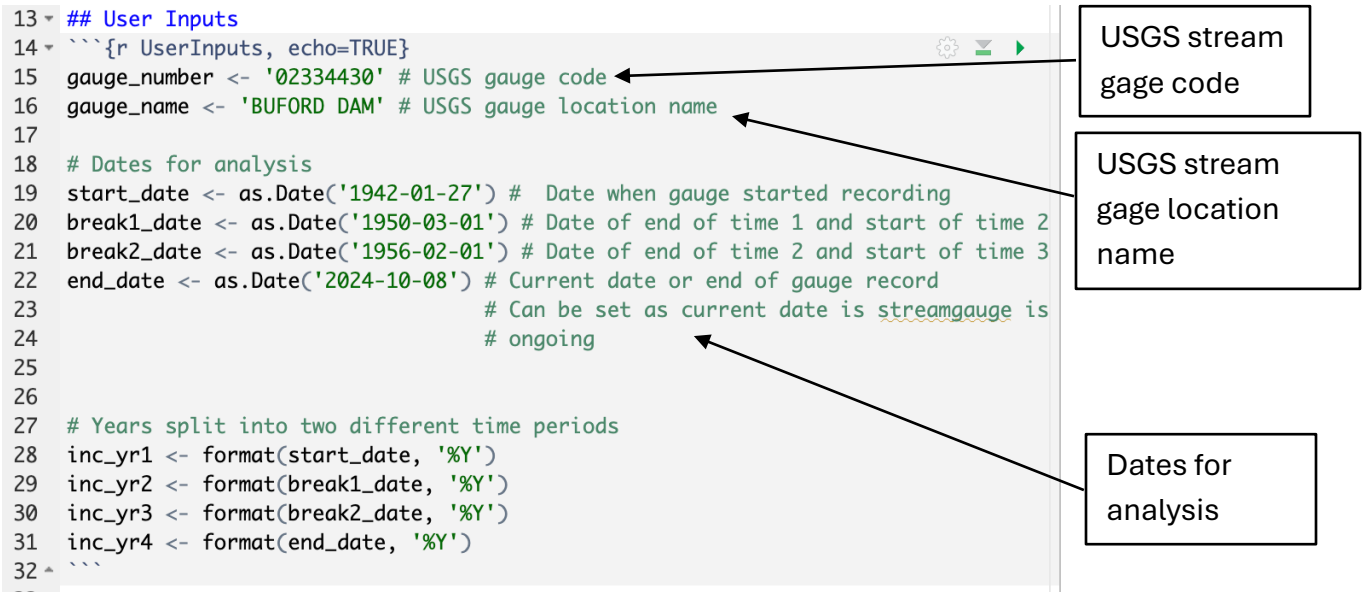


Figure 2. Screen shot of DAMS R Markdown file showing user inputs

2.3 Metrics in DAMS

DAMS contains both hydrologic and geomorphic metrics. Once DAMS accesses the raw stream flow data from the USGS NWIS data portal using the user inputs, the raw stream gage data is fed through R functions that calculate each metric (Table 1 and Table 2) for each year. Metrics are output into R data frames that contain each metric for each calendar year.

Table 1. All metrics in DAMS, source of metrics, necessary data, and description. See Appendix A for a complete description of each metric

Metric or Group of Metrics	Source	Data Required	Notes
Indicators of Hydrologic Alteration	(Richter et al., 1996)	Mean daily flow	33 metrics divided into five groups that measure streamflow based on magnitude, timing, duration, frequency, and rate of change
Annual Median Flow			Annual median of daily mean flows
Annual Mean Flow		Mean daily flow	Annual mean of daily mean flows
Annual Peak Flow		Instantaneous annual peak flow	Instantaneous annual peak flow

Flood Frequency Series		Instantaneous annual peak flow	Shows the size of floods at different recurrence intervals
Annual Top 10% Flow		Mean daily flow	Top 10% of daily mean flows per year
Stream Width	(Smelser & Schmidt, 1998)	Monthly physical measurements	Width of stream at stream gage
Stream Depth	(Smelser & Schmidt, 1998)	Monthly physical measurements	Mean depth of the stream at stream gage
Channel Capacity	(Slater et al., 2015)	Monthly physical measurements	Cross sectional area of stream at stream gage
Mean Stream Bed Elevation (MSBE)	(Smelser & Schmidt, 1998)	Monthly physical measurements	Mean elevation of the stream bed at the stream gage
Sediment Mass Balance	(Schmidt & Wilcock, 2008)	Sediment flow, sediment size, stream discharge	Ratio of pre-dam to post-dam sediment flux estimate derived from Lane's Balance
Flood Magnitude Reduction	(Schmidt & Wilcock, 2008)	Instantaneous annual peak flow	Ratio of pre-dam to post-dam flood at two-year recurrence interval

Table 2. Details of the Indicators of Hydrologic Alteration. Adapted from (Richter et al., 1996)

IHA Group	Regime Characteristic	Individual Metric
Group 1: Magnitude of monthly water conditions	Magnitude Timing	Mean or median value for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual minimum 1-day mean Annual minimum 3-day mean Annual minimum 7-day mean Annual minimum 30-day mean Annual minimum 90-day mean Annual maximum 1-day mean Annual maximum 3-day mean Annual maximum 7-day mean Annual maximum 30-day mean Annual maximum 90-day mean Zero flow days annually
Group 3: Timing of annual extreme water conditions	Timing	Julian day of annual 1 day maximum Julian day of annual 1 day minimum

Group 4: Frequency and duration of high and low pulses	Magnitude Frequency Duration	Number of high pulses per year Number of low pulses per year Mean duration of high pulses each year Mean duration of low pulses each year
Group 5: Rate and frequency of water condition changes	Frequency Rate of Change	Means of all positive differences between each consecutive daily means Means of all negative differences between consecutive daily means Number of changes between increasing and decreasing daily means

IHA Group 2 metrics are calculated by finding the rolling 1-, 3-, 7-, 30-, and 90-day means throughout an entire year (Table 2). The lowest rolling mean for each of lengths of time is the annual minimum for that respective time. The highest rolling mean for each length of time is the annual maximum for that respective time.

For IHA metrics, I use the “IHA” package (Law, 2016). This package contains the functions needed to turn raw data into metrics. For all other metrics, the data either exists from the USGS or I wrote the code myself. Each metric is contained in an R function. This allows each metric to be easily incorporated in the larger structure of DAMS.

2.4 Data Access for DAMS

The United States Geological Survey maintains a network of stream gages on rivers throughout the United States. These stream gages collect flow data which are publicly available in real time. USGS stream gages work by measuring the pressure required to push a set amount of gas through a tube into the stream. The stream stage, or water level is calculated using this pressure measurement, and is referenced to a consistent elevation known as the gage datum (Lurry, 2018). The stream stage is then converted into a stream flow value using a rating curve, which shows the relationship between stream stage and discharge for that particular gage. USGS

technicians create this curve using physical field measurements of stream dimensions and stream flow (Lurry, 2018). These physical measurements are also publicly available (U.S. Geological Survey, 2001).

In order to utilize raw streamflow data in R, it must be input as a data frame. This is done using the “dataRetrieval” package (DeCicco et al., 2018). “dataRetrieval” allows for access to daily mean stream flow, peak annual stream flow, and monthly physical measurements in R. This data allows for most, but not all, of the metrics to be calculated.

To calculate mean stream bed elevation (MSBE), one must account for change in stream gage datum height over time. This information is not called into R using any function that is a part of “dataRetrieval” and must be found for each stream gage on the USGS NWIS legacy site under the “Water Year Summary” tab.

To calculate the sediment mass balance metric, sediment flux data is necessary. Access to this data utilizing “dataRetrieval” is inconsistent as many stream gages do not currently collect sediment flow data. There are some gages throughout the United States that have historic data but few that currently collect sediment flux data. This means this data must be accessed from other sources that “dataRetrieval” cannot access. Sediment flux data must be manually input into DAMS as CSV files. Examples of these repositories of sediment data include the USGS’s Grand Canyon Monitoring and Research Center which monitors sediment flux on select rivers throughout the American Southwest (Grand Canyon Monitoring and Research Center, n.d.).

2.5 Visualization and Graphing

The DAMS R script graphs each metric using the type of graph that is appropriate for the metric. For the most part, each metric is graphed as a time series for all three individual time periods as well as the full time of analysis (Fig. 3). However, there are some metrics where a time series is not the optimal means of visualization. The Julian date of each 1-day maximum and minimum is graphed best as a rose diagram. DAMS produces a rose diagram for each time period in which the Julian day for the maximum and minimum flow is sorted into its week of the year (Fig. 4). These plots allow the user to visualize the change in each metric over time.

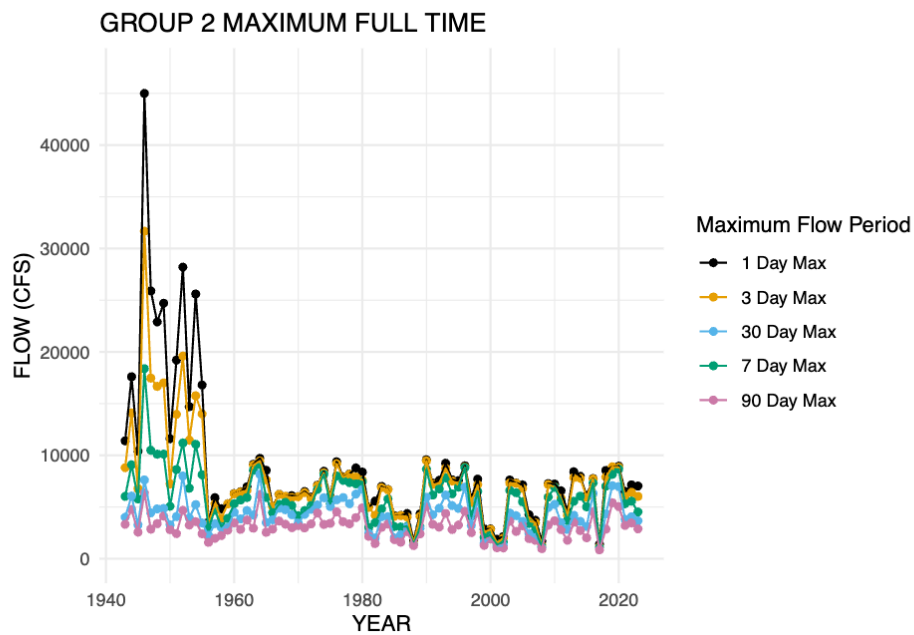


Figure 3. Example time series. IHA Group 2 maximum flow full time plotted.

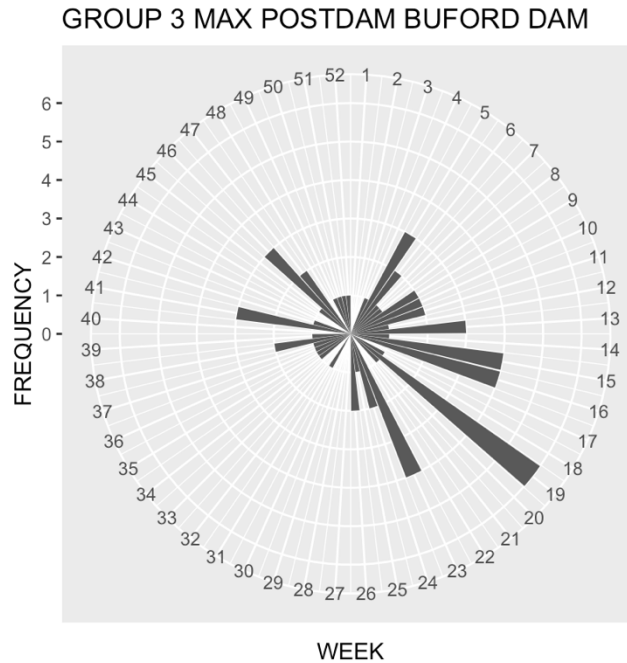


Figure 4. Example Rose diagram. IHA Group 3 maximum post dam plotted.

Flood magnitude reduction and sediment mass balance do not require any visualization. These metrics are ratios between a singular pre-dam value and singular post-dam value.

2.6 Statistical Analysis

Proper statistical analysis is vital to garnering meaning from each metric. Many commonly used statistical tests operate best when data is normally distributed. However, the distribution of hydrologic data is right skewed rather than normal. This is due to hydrologic data having a lower bound of zero and the likely presence of high outliers (Helsel et al., 2002). To combat this, DAMS implements a comprehensive suite of statistical tests (Fig. 5). These statistical tests are run on any metric that is visualized using a time series graph. All statistical tests referenced in this section besides the vector are derived from the “USGS Statistical Methods in Water Resources: Techniques and Methods 4-A3” (Helsel et al., 2002). The set of tests DAMS employs are designed to compare two data sets. This means that each test is run

three times for each metric, comparing each time period in DAMS to the other two time periods.

First, the mean (3) and standard deviation (4) are calculated.

$$\text{Mean: } \bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (3)$$

$$\text{Standard Deviation: } \sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (4)$$

where

- \bar{x} is the sample mean,
- σ is the standard deviation,
- n is the number of data points in the sample,
- x_i is the sample value

Then, a Hodges-Lehman Estimate for difference in medians (5) is run. This produces a value analogous to the difference in medians.

$$\text{Hodges-Lehmann Estimate for Difference in Medians: } \hat{\Delta} = \text{median}[X_i - Y_j] \quad (5)$$

(5)

where

- $\hat{\Delta}$ is the Hodges-Lehman test statistic,
- X_i is the first group's sample values,
- Y_j is the second group's sample values

A Wilcoxon Ranked-Sum test (6) is run to determine if the Hodges-Lehman Estimate is significant. Equation (6) is the test statistic for the Wilcoxon Ranked-Sum test while DAMS utilizes the p-value from this test.

$$\text{Wilcoxon Rank-Sum Test Statistic: } W = \sum_{i \in R_1} R_i \quad (6)$$

where

- W is the Wilcoxon rank-sum test statistic,
- R_i are the ranks of one of the groups

The third step is to determine if the means of time periods being compared are different at a statistically significant level. First, the difference in means (7) is calculated.

<p>Difference in Means: $\Delta_{means} = \bar{x}_1 - \bar{x}_2$ (7)</p> <p style="text-align: center;">where</p> <ul style="list-style-type: none"> - Δ_{means} is the difference in means, - \bar{x}_1 is the mean of the first group, - \bar{x}_2 is the mean of the second group
--

The first step in determining statistical significance of the difference in means is to run a Shapiro-Wilk test (8) on each individual time period to determine if that time period is normally distributed. Equation (8) is the test statistic for Shapiro-Wilk test while DAMS utilizes the p-value from this test.

<p>Shapiro-Wilk Test Statistic: $W = \frac{(\sum_{i=1}^n a_i x_{(i)})^2}{\sum_{i=1}^n (x_i - \bar{x})^2}$ (8)</p> <p style="text-align: center;">where</p> <ul style="list-style-type: none"> - W is the Shapiro-Wilk test statistic, - a_i are the coefficients derived from the normal distribution, - $X_{(i)}$ are the ordered sample statistics, - x_i are the sample values, - \bar{x} is the sample mean

If both time periods being compared are normally distributed, then a Welch's t-test for significance (9) is run. Equation (9) shows the test statistic for Welch's t-test, but the p-value from this test determines if the difference in means is significant.

<p>Welch's t-test Statistic: $t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$ (9)</p> <p>where</p> <ul style="list-style-type: none"> - t is the Welch's t-test statistic, - \bar{x}_i are the sample group means, - s_i are the group variances, - n_i are the sample group sizes
--

If at least one of the time periods is not normally distributed, then a two-sample permutation test (10) for significance is run. Equation (10) shows the test statistic for two-sample permutation test, but the p-value from this test determines if the difference in means is significant.

<p>Two-sample Permutation Test Statistic: $t = \bar{x}_1 - \bar{x}_2$ (10)</p> <p>where</p> <ul style="list-style-type: none"> - t is the two-sample permutation test statistic, - \bar{x}_i are the sample group means

Both the Welch's t-test and two-sample permutation test determine if the difference between the means of each group is statistically significant. In addition to these tests, the percent change between the two time periods in means is also calculated. DAMS implements this full suite of tests because each one tells the user something slightly different about each metric. They allow the user to gain a fuller understanding of each of the metrics.

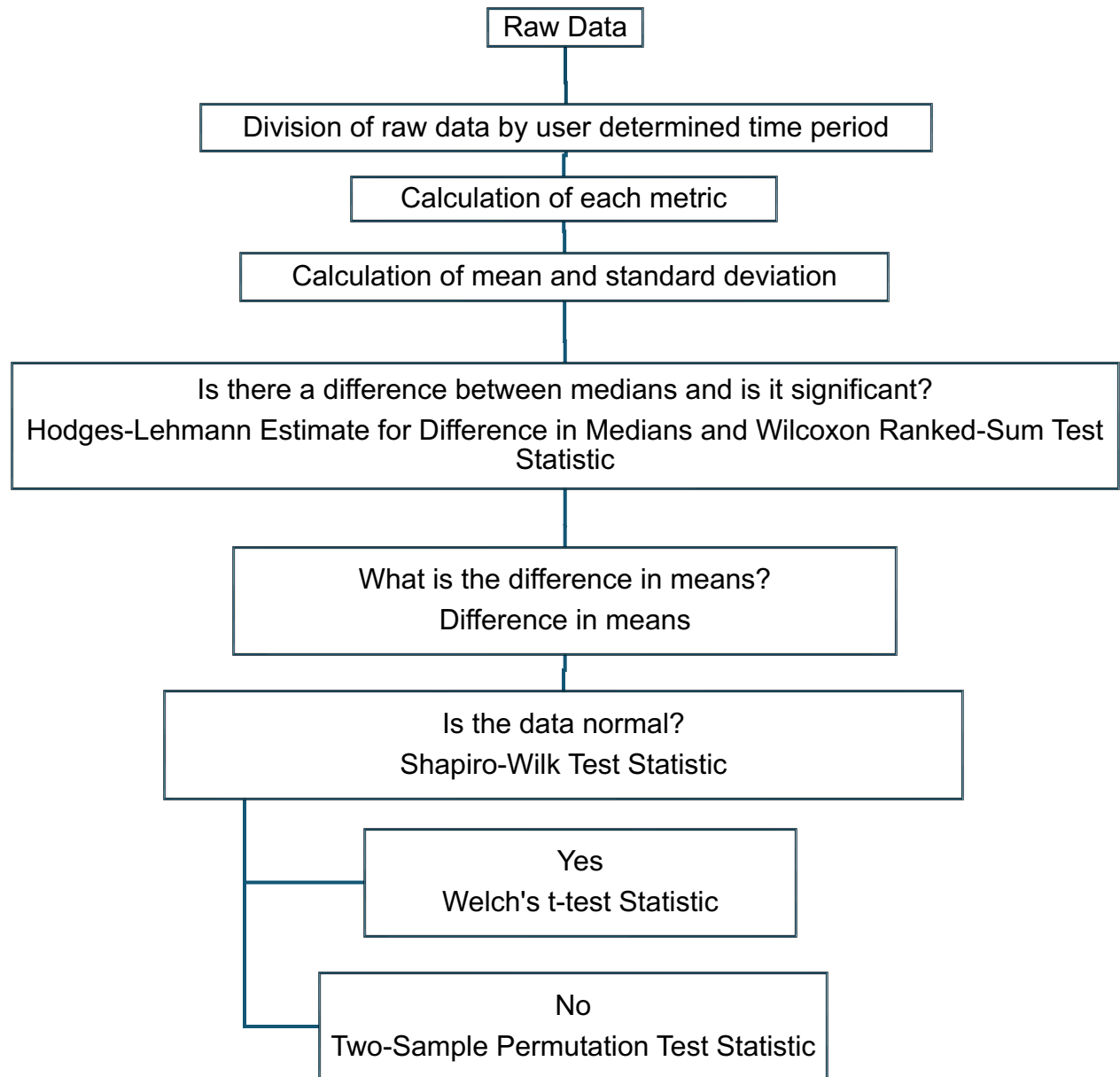


Figure 5. Flow chart showing transformation from raw data input to the completion of statistical tests for most metrics in DAMS.

There are metrics included in DAMS that the statistical tests shown in Fig. 5 do not apply to. For metrics plotted using rose diagrams, the vector mean (11) was calculated alongside standard deviation (Magilligan & Nislow, 2005). This is because

dates at the end of the calendar year are similar to dates at the start of the calendar year but treated as values at the opposite end of the range of data when using Julian day. No statistics were run for flood magnitude reduction and sediment mass balance as these are already ratios that compare two periods of time.

<p>Vector Mean: $X_o = \tan^{-1} \left(\frac{\sum_{i=1}^n \sin \theta_i}{\sum_{i=1}^n \cos \theta_i} \right)$ (11)</p> <p>where...</p> <ul style="list-style-type: none"> - X_o is the vector mean, - n is the sample group sizes, - θ_i is the angle in radians
--

2.7 Outputs

The outputs of DAMS are a pdf containing all graphs for all metrics in DAMS and an excel file with all calculated metrics and relevant statistical tests. The cover page of the pdf is the inputs for DAMS, and statistical tests are labeled with corresponding metric.

3. The Application of DAMS

DAMS was applied to two different impounded rivers in two different geographic and geologic settings. The first dam and associated river is the Buford Dam on the Chattahoochee River in Georgia. The second dam and associated river is the Harris Station Dam on the Kennebec River in Maine.

3.1 Buford Dam and Watershed Information

The Buford Dam, constructed from 1950 to 1956, is an earthen and concrete hydroelectric dam impounding the Chattahoochee River. Located northeast of Atlanta, Georgia, the dam forms Lake Sidney Lanier (Lake Lanier) and is 476.8 meters long and up to 58.5 meters

tall (U.S. Army Corps of Engineers, 2016). Originally authorized by the United States Congress in 1946 for the purposes of hydroelectric power, flood control, navigation, water supply, water quality, fish and wildlife conservation, and recreation, the dam has been under control of the U.S. Army Corps of Engineers (USACE) since its construction (U.S. Army Corps of Engineers, 2016).

The watershed above the Buford Dam includes Lake Lanier and extends up into the Blue Ridge Mountains in Northern Georgia. The watershed is 2693.6 km² (U.S. Geological Survey, 2019) with an elevation ranging from around 243.8 meters at the base of Buford Dam to over 1000 meters in the Blue Ridge Mountains (U.S. Army Corps of Engineers, 2016). Its bedrock geology is mostly metasedimentary rocks with some portions of the watershed being composed of metaigneous rocks. The watershed above the Buford Dam receives roughly 150 cm of precipitation annually, with most of the precipitation occurring during winter and spring months with summer and fall months receiving less precipitation. The higher elevation portions of the watershed receive minimal snow every year (U.S. Army Corps of Engineers, 2016). The snow that does fall does not remain on the ground for extended periods of time and melts within a few days, not affecting any timing of flows in the rivers in the watershed. There are two major rivers that flow through the watershed above the Buford Dam and feed Lake Lanier. The larger of the two is the Chattahoochee River followed by the Chestatee River (U.S. Army Corps of Engineers, 2016).

The river basin downstream of the Buford Dam is one of the largest population centers in the American Southeast. Atlanta is situated downstream of the dam. As of 2010, 4.5 million people lived in the basin downstream of Buford Dam and in the watershed above it (U.S. Army Corps of Engineers, 2016). The U.S. Army Corps of Engineers have identified two major

problems in the basin below the dam. The first is encroachment of built structures into the floodplain. Previously, during periods where Lake Lanier was above conservation pool levels, large amounts of water were released constantly until Lake Lanier was returned to conservation pool levels. Now large amounts of water cannot be released constantly due to the risk of damaging homes and infrastructure in the flood plain (U.S. Army Corps of Engineers, 2016). The second major problem is increased sedimentation due to increased runoff from precipitation events. Increased urban development has caused larger amounts of runoff, which when coupled with increased levels of precipitation, has caused increased sedimentation. This increased sedimentation has caused the downcutting and widening of stream throughout the basin below the Buford Dam and the watershed upstream of it (U.S. Army Corps of Engineers, 2016). The USACE maintains a set of sedimentation ranges in Lake Lanier so they can track aggradation or degradation in the amount of sediment in the lake (U.S. Army Corps of Engineers, 2016). However, this data is not publicly available, and the USACE did not share it with us despite repeated attempts.

Lake Lanier's pool levels are determined by dam release protocols and fluctuate based on the season. The conservation pool elevation, the elevation during normal operations, of Lake Lanier ranges from a minimum of 315.5 meters to a maximum of 326.1 meters during December to April to allow for more inflow during the rainy season and a maximum of 326.4 meters during late April to late September. From late September to December, the maximum conservation pool varies between 326.1 meters and 326.4 meters depending on conditions (U.S. Army Corps of Engineers, 2016). At 326.4 meters conservation pool, Lake Lanier has a surface area of 156.0 km² and a volume of 1.34×10^9 meters³. The flood risk pool elevation is 330.7 meters. Once the

surface of Lake Lanier surpasses this elevation, the use of emergency spillways is likely (U.S. Army Corps of Engineers, 2016).

The hydroelectric plant associated with the Buford Dam is the main control on the timing of daily releases from Lake Lanier. The power plant has two 60-MW generators that run intermittently and one 7-MW generator that runs consistently. The 60-MW generators require a higher flow rate to run than the 7-MW generator and operate for a few hours daily depending on local power needs and the ability to maintain the necessary level of Lake Lanier when releasing water (U.S. Army Corps of Engineers, 2016). The minimum flow through the Buford Dam at all times is currently required to be 750 CFS, but it can decrease to 650 CFS from the months of November to April during periods of drought to maintain required levels in Lake Lanier. Prior to 1976, the minimum required flow through the Buford Dam was 600 CFS (U.S. Army Corps of Engineers, 2016). Because the Buford Dam and its power station are managed by the federal government, most of the information about the watershed upstream of the dam, basin downstream of the dam, and the control of the dam is easy to access and publicly available.

3.1.1 Stream Gage Metadata

Hydrologic and geomorphic change of the Chattahoochee River due to the construction of the Buford Dam was done using data from five different USGS stream gages. All five of the gages have extended stream flow records that date to before the construction of the Buford Dam with four of the five having extensive records of field measurements. Three of the gages are downstream of the Buford Dam while two are upstream of the dam (Table 2). The three downstream gages show change in hydrology and geomorphology due to impoundment, while the two upstream gages act as a baseline reference. Gages acting as a baseline are important because the change they measure cannot be attributed to impoundment. Without baseline gages,

the reason behind the change at downstream gages cannot be isolated. The two upstream gages do not have any upstream impoundments and are on different rivers. The three downstream gages are, following the flow of the river from upstream to downstream: USGS 02334430 Chattahoochee River at Buford Dam, Near Buford, GA; USGS 02334500 Chattahoochee River Near Buford, GA; and USGS 02335000 Chattahoochee River Near Norcross, GA. The two upstream gages are: USGS 02331000 Chattahoochee River Near Leaf, GA and USGS Chestatee River Near Dahlonega, GA. The Norcross stream gage, the furthest downstream from the dam, is downstream of where the Chattahoochee River converges with Suwanee Creek, impacting potential geomorphic or hydrologic alteration (Fig. 6).

Table 2. Metadata of USGS stream gages analyzed associated with the Buford Dam. All information from USGS NWIS.

Gage	Number	River	Downstream or Upstream?	Start of Record	End of Record	Flow Direction	Drainage area (mi²)	Altitude (ft)
Leaf	02331000	Chattahoochee	Upstream	2/21/1940	current	South	150	1219.47
Dahlonega	02333500	Chestatee	Upstream	7/8/1929	current	South	153	1128.74
Buford Dam	02334430	Chattahoochee	Downstream	1/27/1942	current	South	1040	912.01
Buford	02334500	Chattahoochee	Downstream	1/27/1942	9/29/71	South	1060	905.20
Norcross	02335000	Chattahoochee	Downstream	1/1/1903	current	South	1170	878.15

Chattahoochee River near Metro Atlanta
showing major outflows, inflows and monitoring
locations

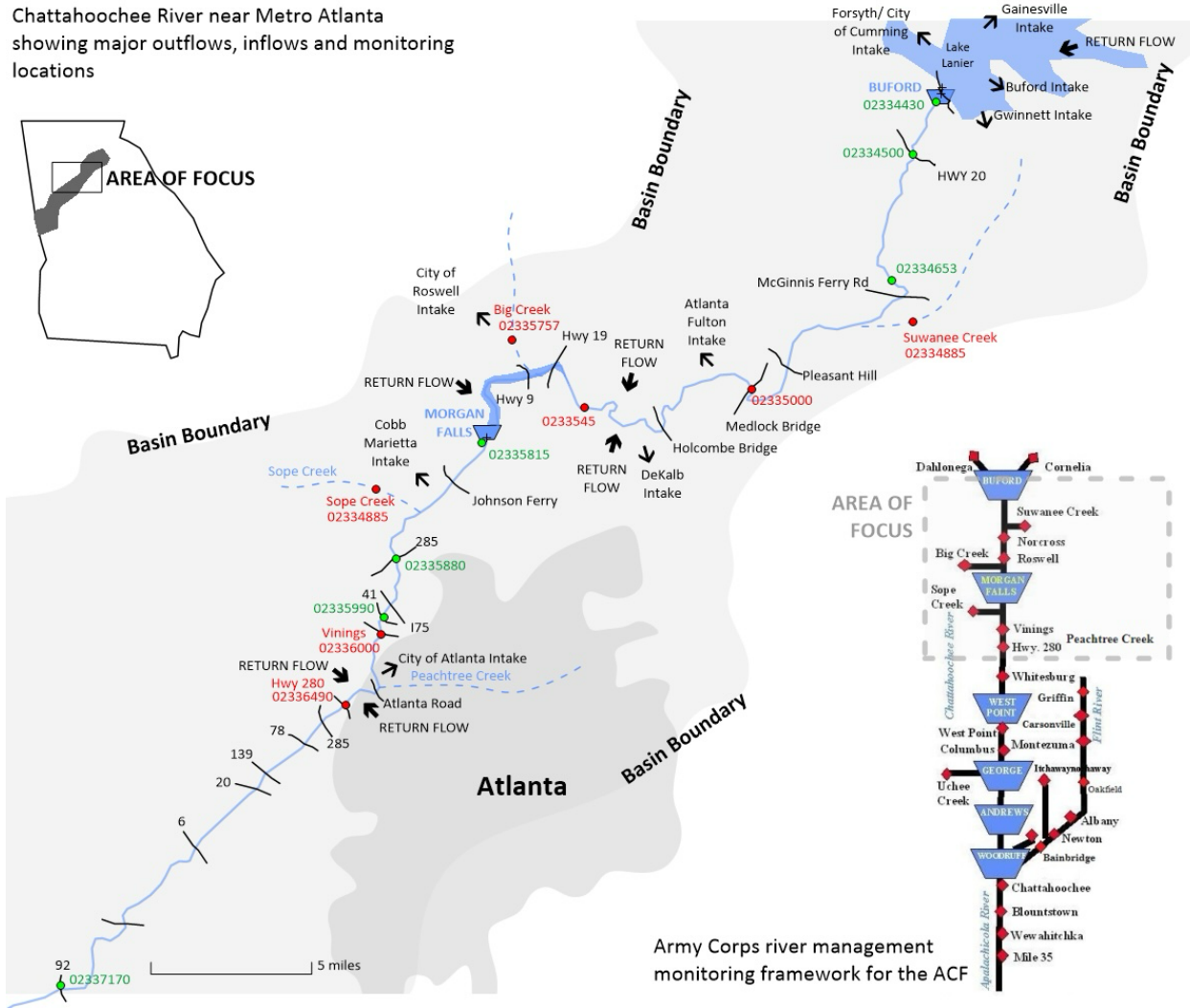


Figure 6. Schematic of inflows, outflows, and stream gages downstream of the Buford Dam. Schematic courtesy of Robert Sobczak, USGS South Atlantic Water Science Center

3.2 Harris Station Dam and Watershed Information

The Harris Station Dam, constructed between 1952 and 1954, is a hydroelectric dam that impounds the Kennebec River in Maine and enlarges the preexisting Indian Pond (Stevens, 2008). The Harris Station Dam is the largest hydroelectric dam in the state of Maine, spanning 270 feet across and 175 feet tall (Stevens, 2008). It is owned and operated by Brookfield Renewable Partners, and the power generated by the power plant is distributed by Central Maine

Power Co. The dam has four separate turbines that have the capacity to produce 76.4 MW of electricity at peak generating capacity (Hydropower Reform Coalition, n.d.).

The releases from the Buford Dam are controlled by Brookfield Renewable Partners with input from commercial rafting companies that raft downstream of the dam. This means that the in addition to the standard daily high releases for the primary purpose of generating power, there are scheduled releases throughout the Summer and Fall months that have double the flow of standard daily high releases during the same time period (SafeWaters by Brookfield Renewable, 2025). Because the Harris Station dam is privately owned and controlled, there is a lack of detailed public information about the control of flow through the dam.

The watershed upstream of the Harris Station Dam is 1384 square miles with a maximum elevation of 3722 feet (U.S. Geological Survey, 2019). The elevation of Indian Pond, which is the lowest point in the watershed upstream of the Harris Station Dam, is roughly 955 feet (U.S. Geological Survey, 1981). Twenty percent of the watershed is covered in bodies of water and wetlands, and the watershed receives 110 centimeters of precipitation annually (U.S. Geological Survey, 2019). During the winter months, snow accumulates in the watershed, which creates temporary storage of the water that then melts in the spring. The watershed upstream of the Harris Station Dam and the river basin downstream of the dam are composed of various metamorphic rock facies (*Bedrock Geologic Map of Maine*, 1985). Generally, the public information about the watershed upstream and river basin downstream of the Harris Station Dam is far less centralized and consolidated than the same information related to the Buford Dam.

3.2.1 Stream Gage Metadata

Data from three different USGS stream gages were analyzed to determine any geomorphic or hydrologic change due to the construction of the Harris Station Dam on the Kennebec River. The stream gage at The Forks is the one stream gage downstream of the dam. This gage provides information about how the impoundment has affected the river. As there are no stream gages upstream of the Harris Station Dam with an extended record, unimpounded stream gages from a similar region in watersheds with similar characteristics and long periods of record from before and after the construction of the Buford Dam were used as reference gages (Table 3). Gages with the most similar drainage area and mean percent of watershed logged per year from 1999 – 2012 (GAGES-II, 2011) were selected.

Table 3. Metadata of USGS stream gages analyzed associated with the Harris Station Dam. All information from USGS NWIS while logging data is from GAGES-II dataset.

Gage	Number	River	Reference or Downstream	Start of Record	End of Record	Drainage area (mi²)	Altitude (ft)	Mean % of watershed logged per year from 1999-2012
Fort Kent	01013500	Fish	Reference	7/29/1903	current	870	510.64	0.786428571
Mattawamkeag	01030500	Mattawamkeag	Reference	10/1/1934	current	1419	210.62	0.192857143
The Forks	01042500	Kennebec	Downstream	10/1/1903	current	1590	568.58	0.531428571

3.3 Use of precipitation data

One of the major controls on stream flow is precipitation. Increases in precipitation often cause increases in stream flow, and precipitation decreases often cause decreases in streamflow. This effect is increases when there is minimal stream flow (Wigley & Jones, 1985). In order to fully understand what affect the construction of the Buford Dam and Harris Station Dam had on their respective rivers, I accessed monthly precipitation data for the watershed above each stream

gage used for the analysis. Understanding changes in precipitation allowed me to isolate what changes in streamflow could be attributed to changes in climate. Data was sourced from the PRISM Group at Oregon State University (Oregon State University, 2023), and contained precipitation data from 1895 to 2023 for each watershed. Pre-dam monthly precipitation means were compared to post-dam monthly precipitation means using the same statistical tests utilized in DAMS. This gives a more comprehensive understanding of the causes behind any change in hydrologic regime between pre-dam and post-dam conditions.

4. Buford Dam Results

Stream flow data from two gages upstream of the Buford Dam and three gages downstream of the Buford Dam was run through DAMS. All data from before the start of the construction of the dam in 1950 was considered pre-dam, and all data from after the completion of the construction of the dam in 1956 was considered post-dam.

4.1 IHA Group 1

Upstream of the Buford Dam, there is no significant change in any of the months of the year, except for a significant increase in flow at the Dahlenega gage in October. However, downstream of the dam, there was a significant decrease in mean monthly flow during January, February, and March. The greatest decrease was 57.3% at the Buford gage during February, and the smallest decrease was 23.4 % at the Norcross gage in January. It is worth noting that the decrease at the Norcross gage during these months' ranges from 23.4% - 27.7% while the decrease at the Buford and Buford Dam gages ranges from 39% - 57.3%. There was a significant decrease in flow during December at the Norcross gage at similar amounts to the January – March decrease. There is a significant increase in flow values from pre-dam to post-dam

construction at the Norcross gage during August, September, October, and November, while this increase was only significant during October for the Buford and Buford Dam gages. Significant increases ranged from 26.65% - 56.5% (Fig. 7).

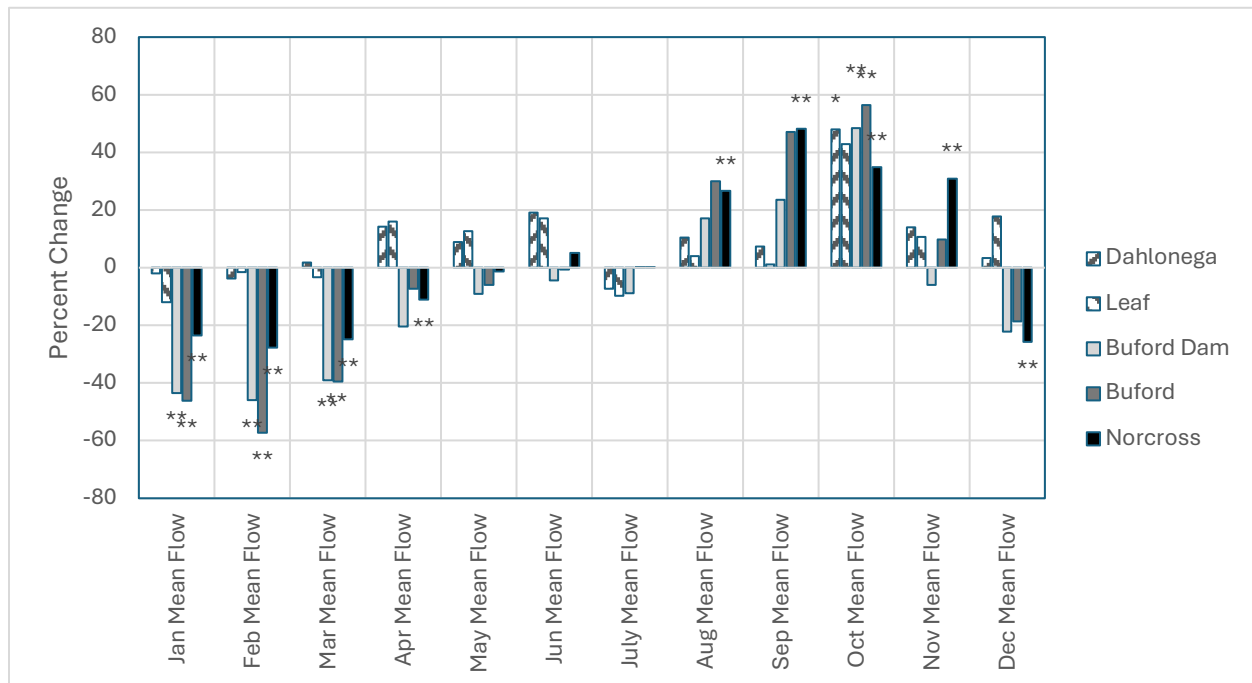


Figure 7. Change in mean of daily flow for each month from before dam construction to after construction of the Buford Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

There was no significant change between pre-dam construction and post-dam construction in the median of mean daily flows for each month at gages upstream of the dam, but there was significant change at gages during certain months downstream of the dam. There was a significant decrease in February at Buford Dam of 46.4%. There were significant increases during July to November at the Norcross gage ranging from 18.5% - 84.7% and during August to October at the Buford Dam and Buford gages ranging from 53.6% - 121.1%

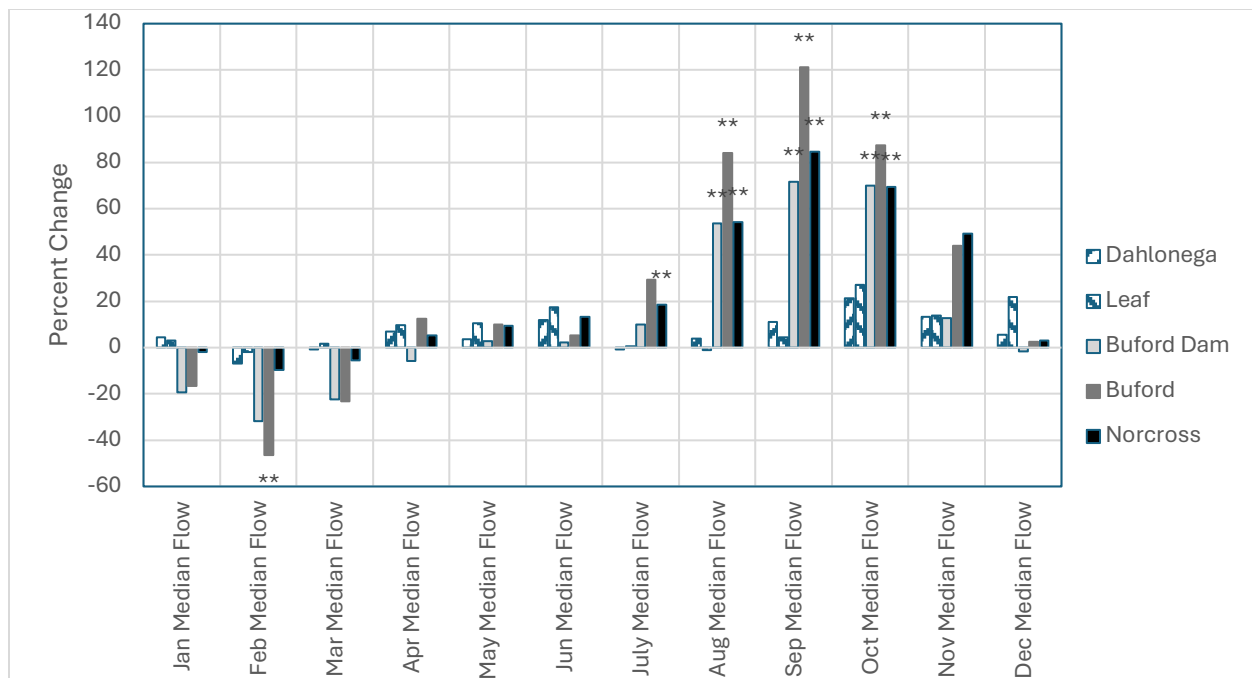


Figure 8. Change in median of daily flow for each month from before dam construction to after construction of the Buford Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

4.2 IHA Group 2

Upstream of the Buford Dam, there was no significant change in any of the means of the 1-, 3-, 7-, 30-, or 90-day rolling minimum or maximums per year between pre- and post-impoundment conditions. However, there was a significant change at downstream gages. Generally, there was a decrease in minimum and maximum values. This was a significant decrease at all downstream gages in the 1-day minimum and maximum, 3-day maximum, and 7-day maximum. Other metrics that experience a significant decrease at one of the three downstream gages are the 3-day minimum, 30-day maximum, and 90-day maximum. It is worth noting that there was a significant increase at the Norcross gages of 18.36% and 18.56% for 7-day min and 30-day min respectively (Fig. 9).

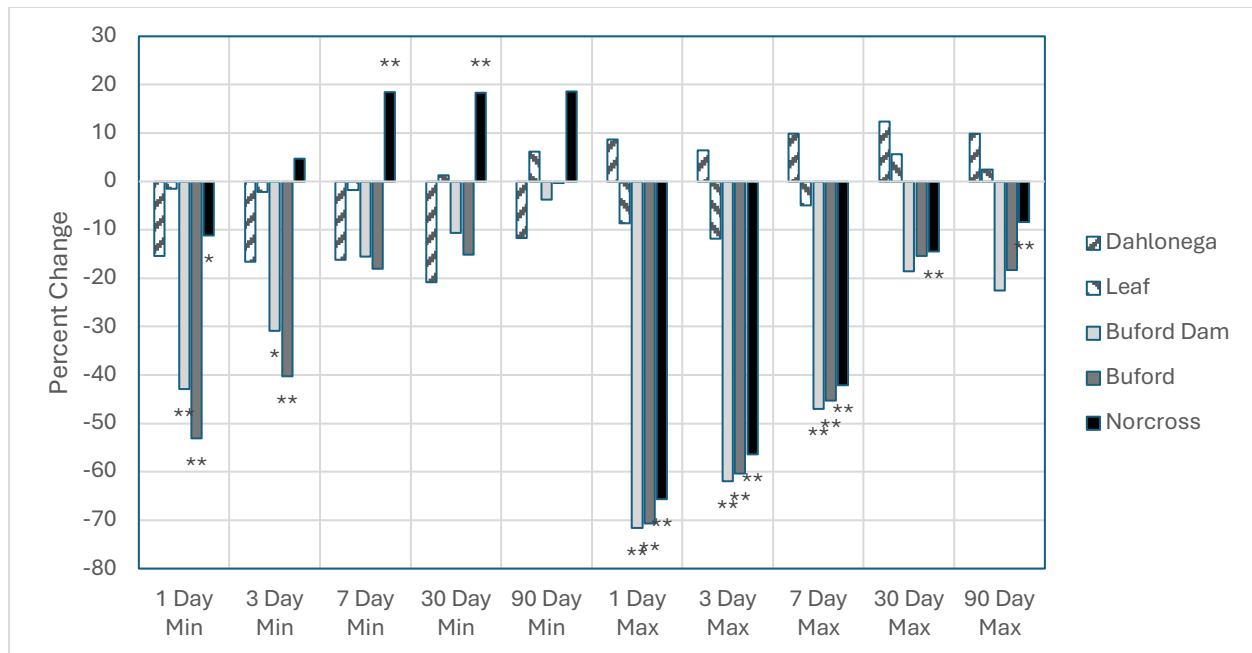


Figure 9. Change in magnitude and duration of extreme flows from before dam construction to after construction of the Buford Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

4.3 IHA Group 3

At four of the stream gages there is a change in the date of the maximum daily flow. This shift happens at all gages but the Norcross gage (Table 4). In pre-dam conditions, the day of the maximum flow was in January. The day of maximum flow ranges from late February to late March post-dam construction. In pre-dam conditions, the date of the minimum daily flow was from late September to late October across all gages (Table 4). In post-dam conditions, these dates stay fairly consistent at the two upstream gages and at the Norcross gage. However, at the Buford Dam and Buford gages, the dates of the minimum daily flow are in March post dam construction.

Table 4. The mean Julian Day and standard deviation for the daily maximum and minimum flows for pre- and post-Buford Dam construction conditions

	Max Pre-dam Mean	Max Pre-dam SD	Max Post-dam Mean	Max Post-Dam SD	Min Pre-Dam Mean	Min Pre-Dam SD	Min Post-Dam Mean	Min Pre-Dam SD
Dahlongega	25.8	90.8	73.2	62.4	291.5	87.5	276.6	17.9
Leaf	20.4	77.0	56.4	40.8	282.5	57.3	275.7	24.3
Buford Dam	16.9	75.6	80.6	68.7	294.0	52.5	87.6	187.2
Buford	16.9	75.6	55.5	45.4	294.0	52.5	66.4	184.2
Norcross	38.2	85.3	35.4	N/A	267.8	50.1	251.0	N/A

4.4 IHA Group 4

Upstream of the Buford Dam, there was a significant decrease in the number of low flow pulses each year from pre-dam conditions to post-impoundment conditions. The decrease at the Dahlongega gage was 20.8%, and the decrease at the Leaf gage was 34.3%. Downstream of the dam, there was a significant increase in the number of low flow pulses per year after dam construction, ranging from a 293.2% increase to a 786.9% increase. Upstream of the dam, there was no significant change in the number of high flow pulses. However, downstream of the impoundment, there was a significant increase in the number of high pulses each year, ranging from 62.4% to 95.3%. Downstream of the impoundment, there was a significant increase in the length of each high pulse, ranging from 113.8% to 119.2% at the gages closest to the dams and 27.8% at the gages furthest from the dam. Upstream of the dam, there was a significant increase in the length of high pulses that was 21.2%, but only at the Dahlongega gage.

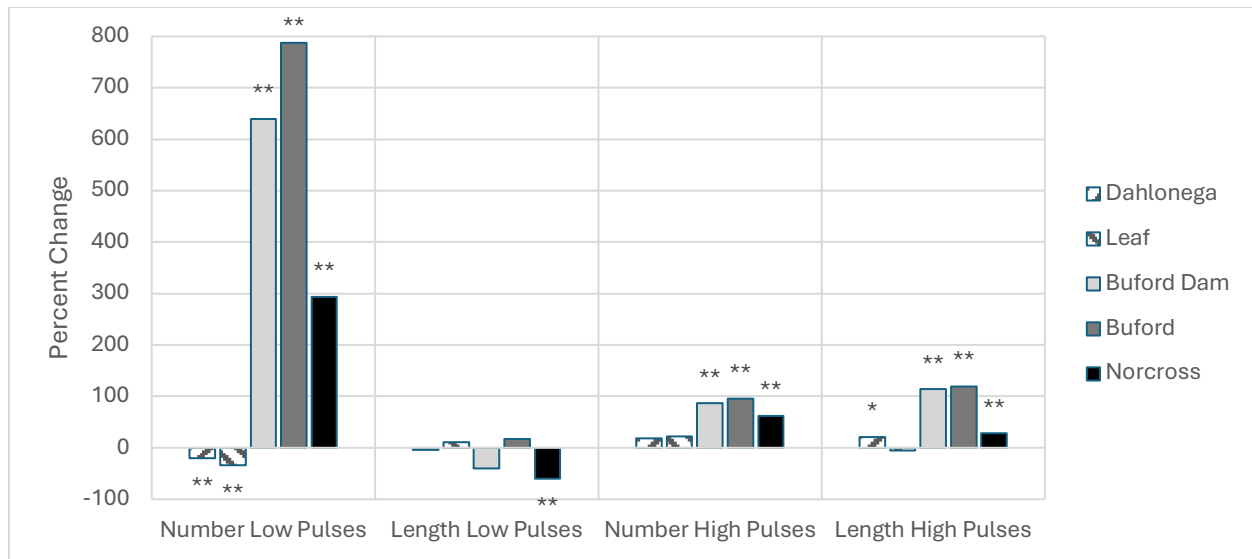


Figure 10. Change in frequency and duration of high and low pulses from before dam construction to after construction of the Buford Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

4.5 IHA Group 5

Alteration in the rate change of flow and frequency of change of flow from pre-impoundment to post-impoundment conditions was inconsistent from gage to gage, especially downstream of the gage. Upstream of the gage, the only significant change was a decrease in the mean rate of flow increase by 44.2% and an increase of the number of reversals by 8.5% at the Dahlenega gage. Downstream, there is a lack of consistency in significant results. The only metric that shows change in the same direction for all gages with significant results is fall rate. The fall rate significantly increases at the Buford Dam gage and the Norcross gage by 91.2% and 137.4%, respectively.

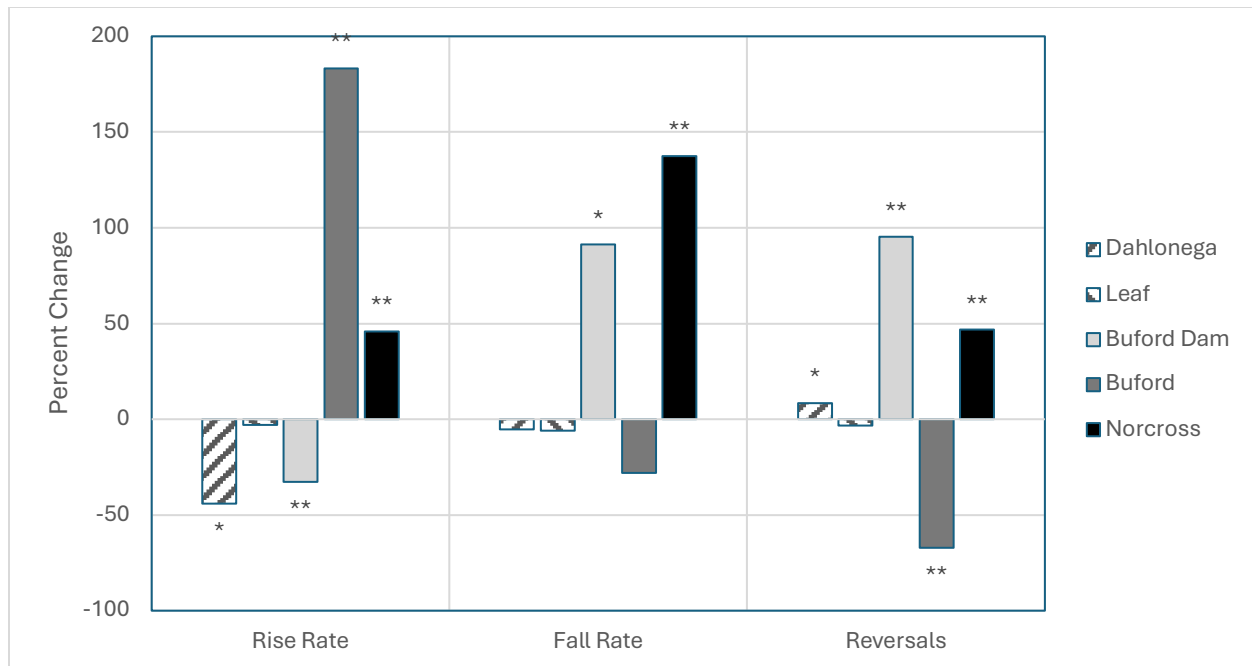


Figure 11. Change in rate and frequency of change in flow from before dam construction to after construction of the Buford Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

4.6 Median and Mean

At gages upstream of the Buford Dam, there is no significant change in either the median or mean from pre-dam to post-dam conditions. Downstream, all significant changes for both the annual median and annual mean flow are a decrease. The only significant result for annual median flow is at the Buford Dam gage, which shows an 18.9% decrease. The Buford Dam and Buford gages show a significant decrease in annual means, which are 19.4% and 17.9%, respectively.

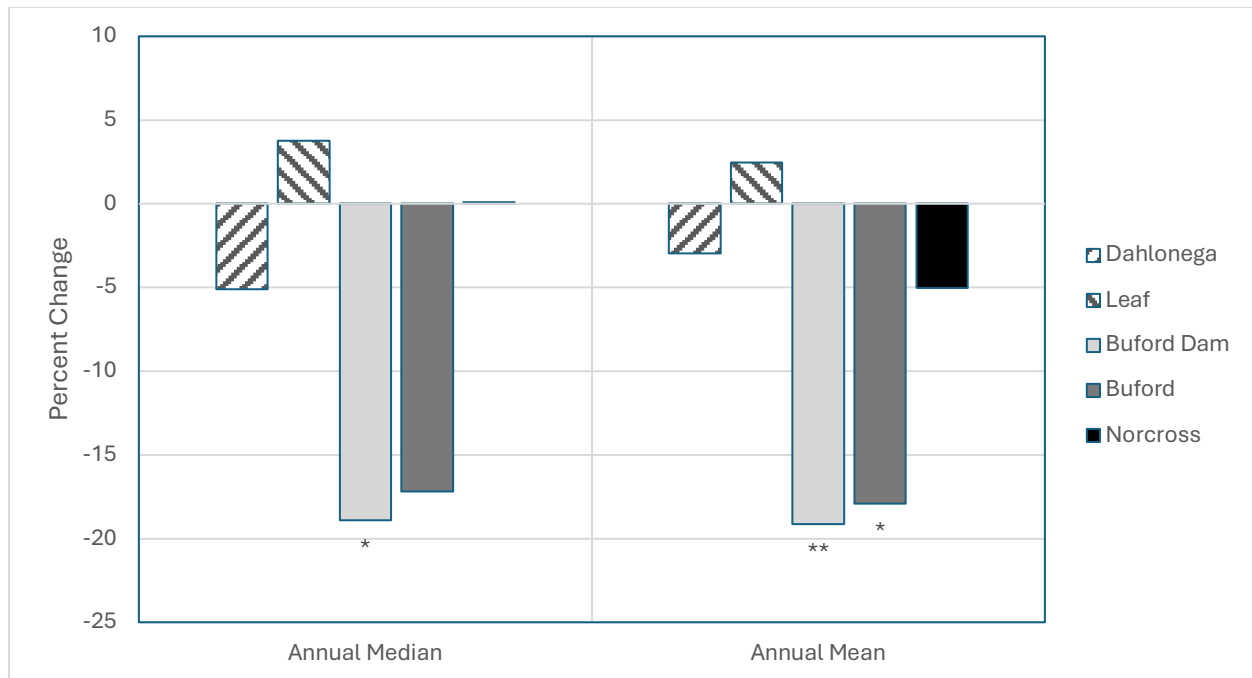


Figure 12. Change in annual mean and median flow from before dam construction to after construction of the Buford Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

4.7 Peak Flows and High Flows

Annual peak flow data was only available at the two upstream stream gages and the Buford and Norcross gages downstream. Neither of the upstream gages recorded a significant change in peak flows from pre- to post-dam conditions. At both the Buford and Norcross gages, there was a significant decrease of 63.7% and 56.7%. The difference between mean of the top 10% of mean daily flows at upstream gages is only significant at the Dahlongega gage, which had an 8.1% increase. All three downstream gages had a decrease in the mean of the top 10% of mean daily flows from pre-dam to post-dam conditions, ranging from 24.3% to 27.2%. The flow value exceeded 10% of the time showed significant increase at both Dahlongega and Leaf, the upstream gages. The former increased by 6.9% while the latter increased by 5.8%. The Buford and Norcross downstream gages also saw significant increases of 9.5% and 10.2%, respectively (Fig. 13).

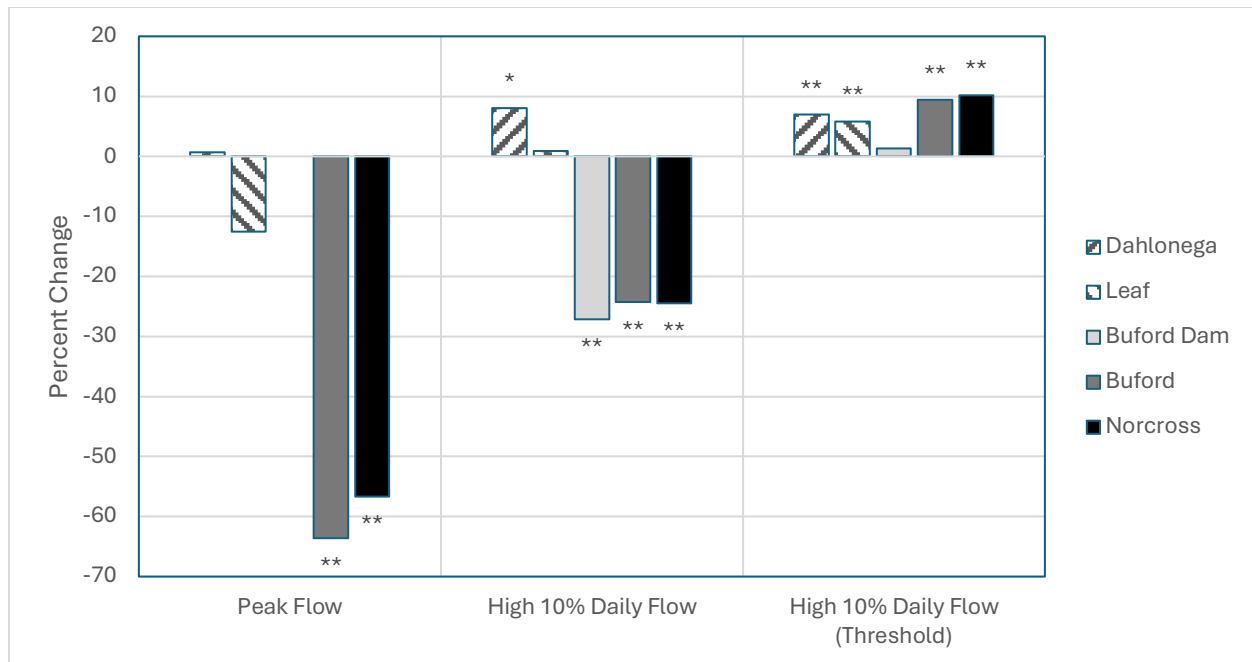


Figure 13. Change in annual instantaneous peak flow, mean of the highest 10% of daily flow annually, and the threshold for highest 10% of daily flow annually from before dam construction to after construction of the Buford Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

4.8 Geomorphology

There is a lack of consistency in the geomorphological changes due to the construction of the Buford Dam as measured by field measurements taken at the stream gages in question. No field measurements were recorded at the Buford Dam stream gage. Alteration to channel capacity upstream of the Buford Dam is only significant at the Leaf gage, which saw a 11.2% increase. Downstream of the dam, the only gage to show a significant change in channel capacity is the Norcross gage, which saw a decrease in capacity by 38.1%. Alteration in mean width is only significant at the Leaf and Norcross gages. The Leaf gage saw a 4.8% increase in width while the Norcross gage saw a 5.1% increase in stream width from pre-dam to post-dam conditions. Alteration in mean depth of the river channel is only significant at the two downstream gages where data collection occurred. The Chattahoochee River experienced a 28.1% decrease in depth

at the Buford gage and a 36.4% decrease in depth at the Norcross gage. Mean stream bed elevation (MSBE) had minor but significant changes at the two upstream gages. MSBE increased at Dahlonega by 1.2% but decreased by .8% at Leaf. MSBE decreased by .1% at the Buford gage and saw no significant change at the Norcross gage (Fig. 14). It is worth noting that the MSBE is measured based on the elevation of the gages so small percentage changes can still be major alterations in MSBE.

4.9 Sediment Mass Balance

All five gages being analyzed to measure alteration of the Chattahoochee River due to the construction of the Buford Dam do not collect continuous sediment flow data. This means that DAMS cannot assess the sediment mass balance of the Chattahoochee River.

4.10 Flood Reduction Magnitude

As annual instantaneous peak flows were collected only at Dahlonega, Leaf, Buford, and Norcross, these are the only gages where DAMS could calculate flood reduction magnitude. The flood reduction magnitude at the upstream gages ranged from 1.26 to 1.67. Downstream, the flood reduction magnitude ranged from 1.97 to 2.22.

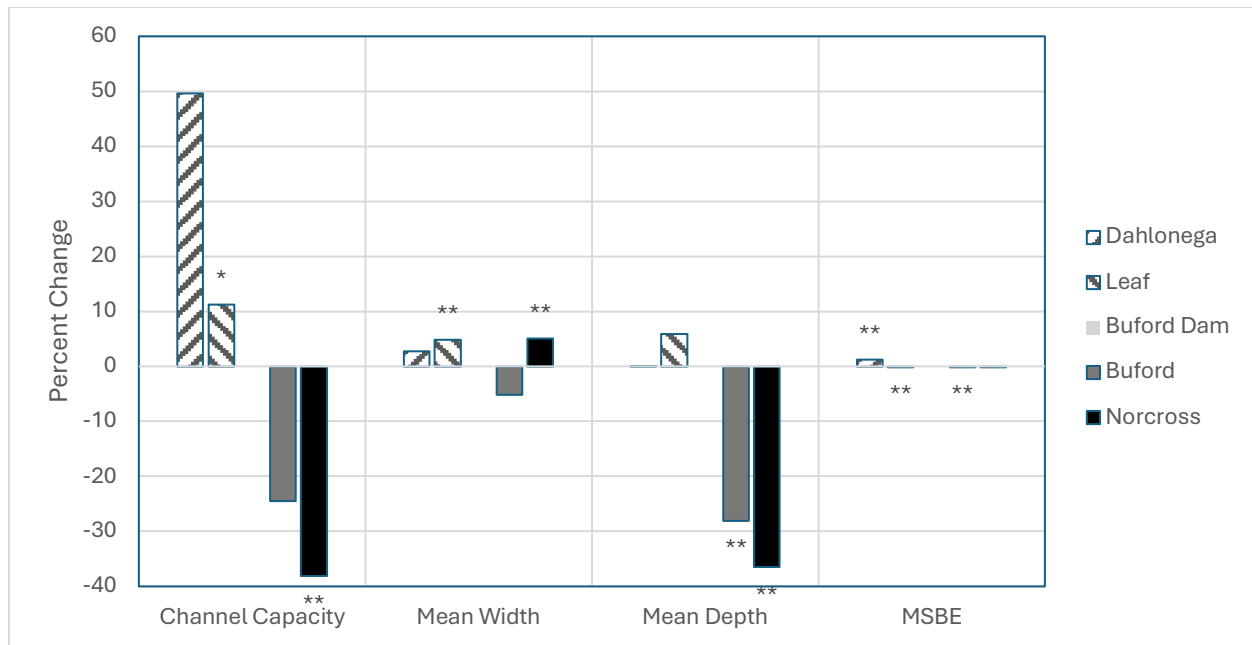


Figure 14. Change in geomorphology derived from field measurements from before dam construction to after construction of the Buford Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

Table 5. Flood magnitude reduction from before dam construction to after dam construction of the Buford Dam at stream gages upstream and downstream of the impoundment.

Gage		Flood Magnitude Reduction
Dahlenega		1.260794473
Leaf		1.166666667
Buford Dam	N/A	
Buford		2.219917012
Norcross		1.970338983

4.11 Precipitation

Precipitation in watersheds draining to both upstream and downstream gages increase from pre-dam to post-dam time periods during the months of April, September, and October, but the only significant increase during these months is in April at the watershed above the Buford gage and in September in the watershed above the Norcross gage. The only other significant change in precipitation was in November in the watershed above the Norcross gage. However,

during November, there is a nonsignificant decrease in precipitation between pre-dam and post-dam time periods in the two other watersheds above the downstream gages (Fig. 15)

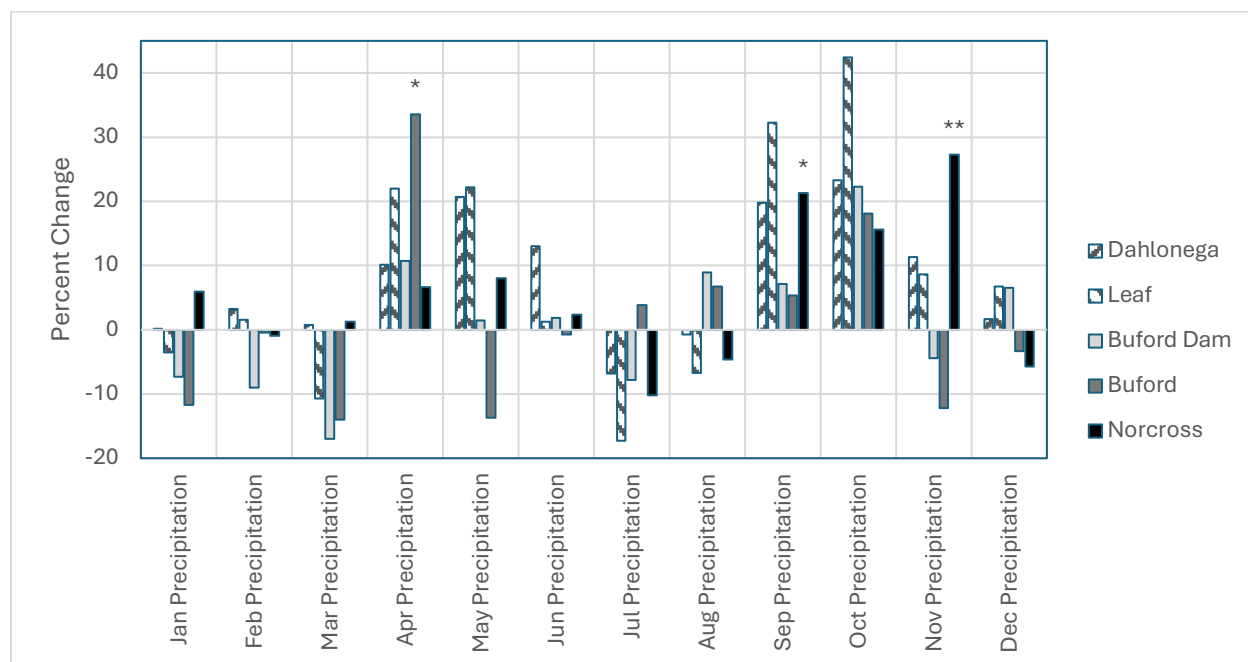


Figure 15. Change of monthly precipitation from before dam construction to after construction of the Buford Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

5. Harris Station Results

Stream flow data from two reference gages and one gage downstream of the Harris Station Dam was run through DAMS. All data from before the start of the construction of the dam in 1952 was considered pre-dam, and all data from after the completion of the construction of the dam in 1954 was considered post-dam.

5.1 IHA Group 1

There is significant change in the monthly mean of mean daily flows at the reference and downstream gages between pre-1952 and post-1954 conditions. The Forks gage saw a significant increase in mean of mean daily flow in all months except for May, June, July, and August. The

increase ranged from 16.8% in September. to 46.9% in February. July and August had significant decreases in mean of mean daily flow. The former had a 15.8% decrease, and the latter had a 9.5% decrease. Significant increases at the Fort Kent gage only occurred from December to April. Each of these months saw an increase in mean of mean daily flow ranging from 33.1% in Dec. to 63.1% in February. There was a significant decrease of 17.2% in July at the Fort Kent gage. The Mattawamkeag gage had significant increase in mean of mean daily flows in February, April, and August. This increase ranges from 16.6% in April to 95.1% in August. (Fig. 16).

There were also significant changes in the median of mean daily flow for many of the months at the reference and downstream gages. The Forks gage saw a significant increase in median of mean daily flow after dam construction for all months except for May, June, July, and August. The increase ranges from 17.4% in September to 49.5% in February. There is only a significant decrease during July, which had a decrease of 14.8%, and August, which had a decrease of 11.5%. The only significant changes in median of mean daily flows at the Fort Kent gage are increases from December to April. This increase ranges from 33.1% in Dec. to 63.1% in February. There is only significant change at the Mattawamkeag gage is increases in February, April, August, and September. The increases range from 20.4% in April. to 85.8% in September. (Fig. 17).

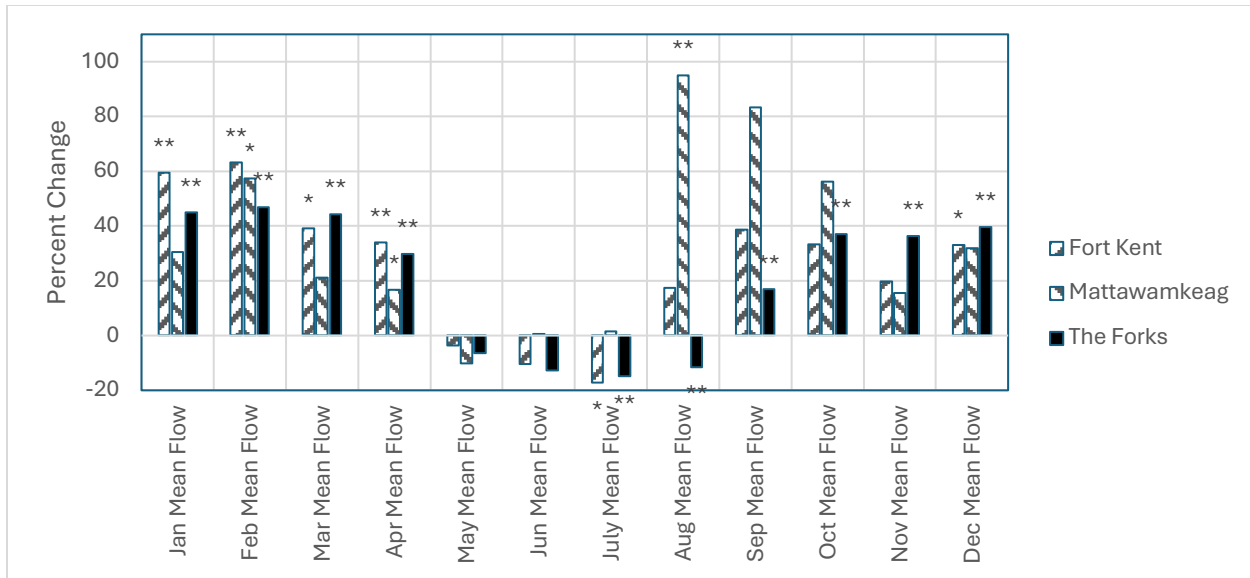


Figure 16. Change in mean of daily flow for each month from before dam construction to after construction of the Harris Station Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

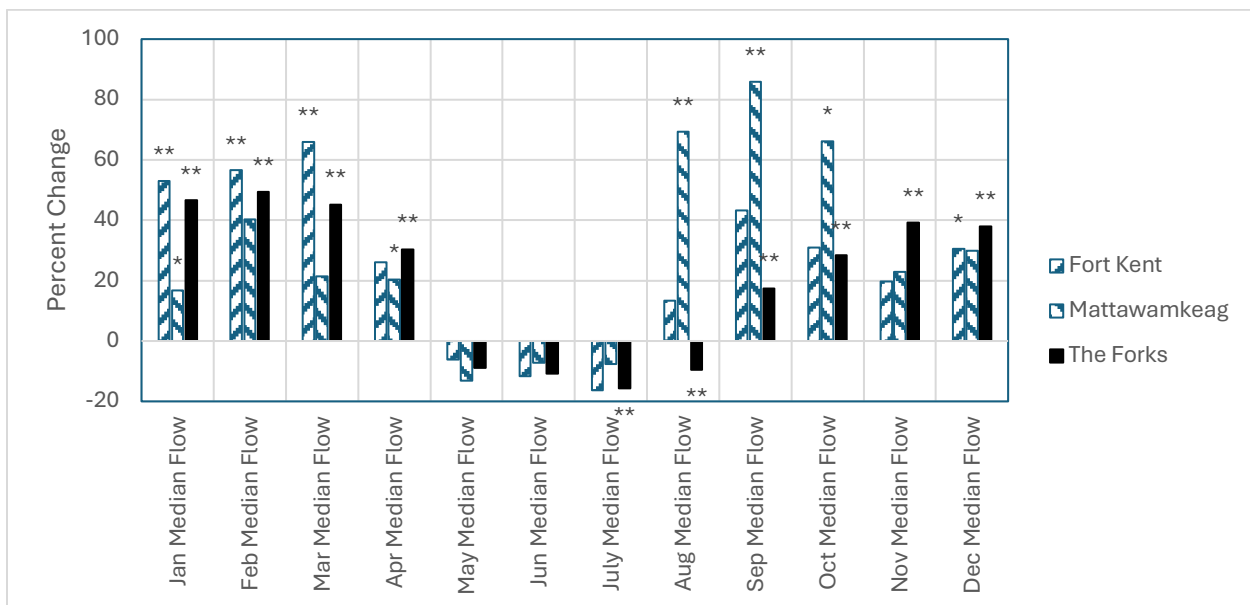


Figure 17. Change in median of daily flow for each month from before dam construction to after construction of the Harris Station Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

5.2 IHA Group 2

There is a significant change in the magnitude and duration of extreme flows at both the reference gages and the downstream gages between pre-1952 and post-1942 conditions. There are significant increases for all metrics in Group 2 except 90-day max at the Fort Kent gage. This increase ranges from 11.3% for 30-day max and 36.8% for 90-day min. The Mattawamkeag gage only had significant change for the 90-day min, which increased by 49.1%. There is only significant change at The Forks gage for 3-day min, 7-day min, 30-day min, and 90-day min. Each saw an increase, which ranged from 17.7% for 3-day min and 36.5% for 7-day min (Fig 18).

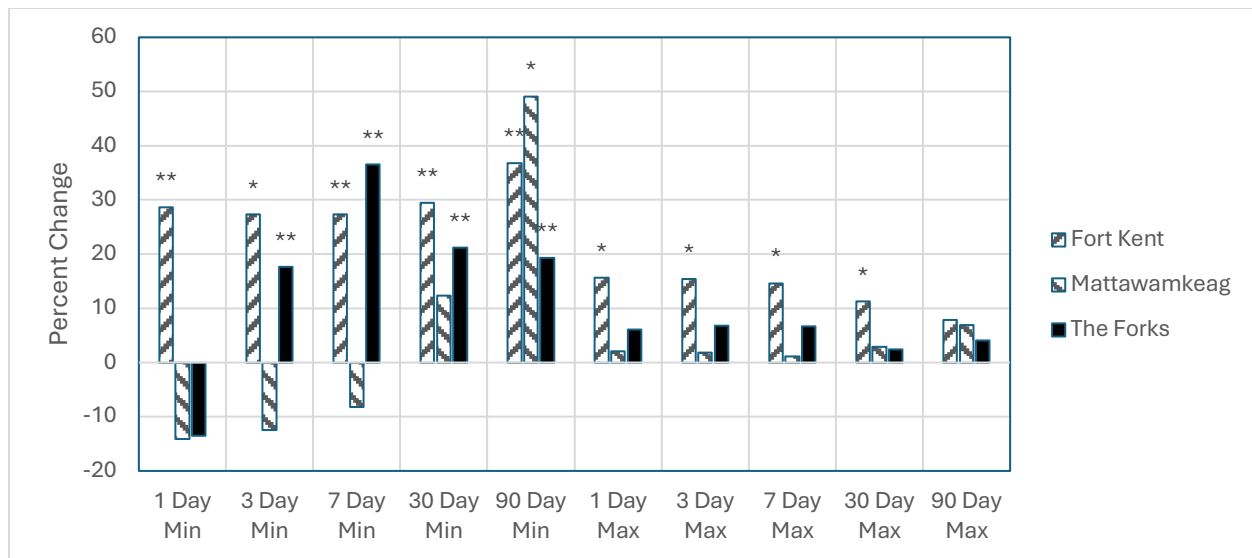


Figure 18. Change in magnitude and duration of extreme flows from before dam construction to after construction of the Harris Station Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

5.3 IHA Group 3

Pre-1952, the date of the annual daily maximum ranges from mid-April to mid-May. Post-1954, the day of the annual daily maximum shifted to early to mid-April at the reference gages but did not alter at the downstream gage (Table 6). The date of the annual daily minimum

flow ranges from early October to the end of December before the construction of the Harris Station Dam and shifts earlier at two of the three gages (Table 6).

Table 6. The mean Julian Day and standard deviation for the daily maximum and minimum flows for pre- and post-Harris Station Dam construction conditions

	Max Pre-dam Mean	Max Pre-dam SD	Max Post-dam Mean	Max Post-Dam SD	Min Pre-Dam Mean	Min Pre-Dam SD	Min Post-Dam Mean	Min Pre-Dam SD
Fort Kent	120.4	41.8	102.8	N/A	317.1	175.8	287.2	N/A
Mattawamkeag	107.2	51.5	95.2	N/A	275.3	100.9	274.1	N/A
The Forks	139.4	59.5	135.9	N/A	364.8	214.1	315.1	N/A

5.4 IHA Group 4

The change in the frequency and duration of high and low pulses is only significant at The Forks gage for all IHA Group 4 metrics and at Mattawamkeag for high pulse metrics. The number of high and low pulses at The Forks both increased, by 166.4% and 128.0% respectively. The length of high and low pulses both decreased, by 68.2% and 38.6% respectively. At Mattawamkeag, the number of high pulses increased by 41.4%, and the length of the high pulses decreased by 33.5%. There was no significant change in the frequency and duration of high and low pulses at Fort Kent (Fig. 19).

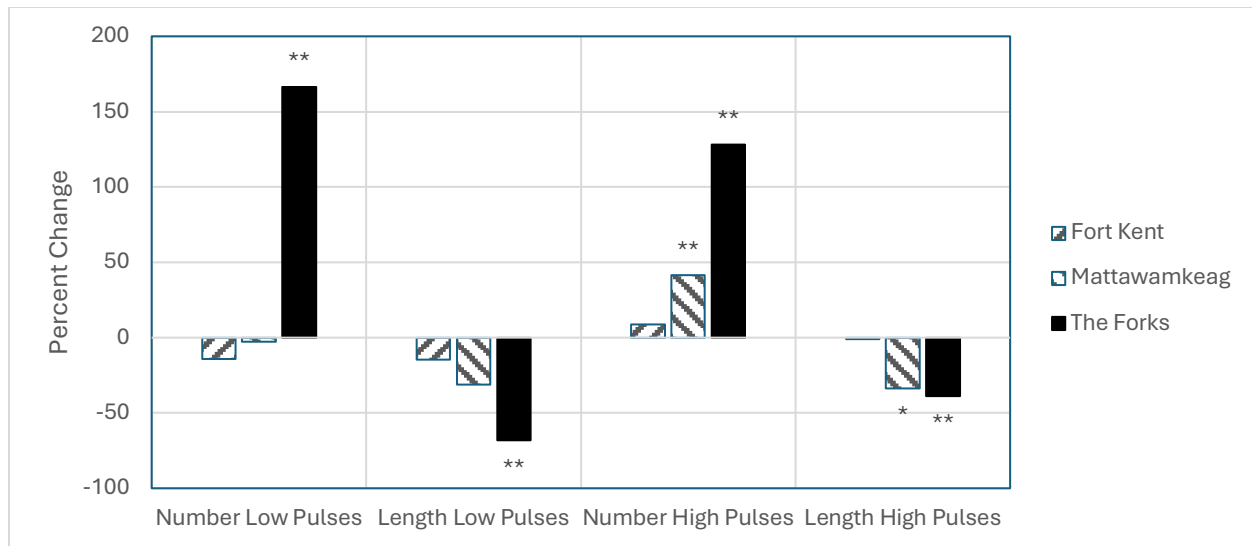


Figure 19. Change in frequency and duration of high and low pulses from before dam construction to after construction of the Harris Station Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

5.5 IHA Group 5

There is significant change in the rate and frequency of change in flow at both the Mattawamkeag and The Forks gage. At Mattawamkeag, the rise rate increased by 41.3%, the fall rate increased by 45.2%, and the number of reversals per year increased by 7.2%. At The Forks, the rise rate increased by 116.8%, the fall rate increased by 202.9%, and the number of reversals per year increased by 78.8%. There was no significant change in the rate and frequency of the change in flow from pre-1952 to post-1954 conditions at Fort Kent (Fig. 20).

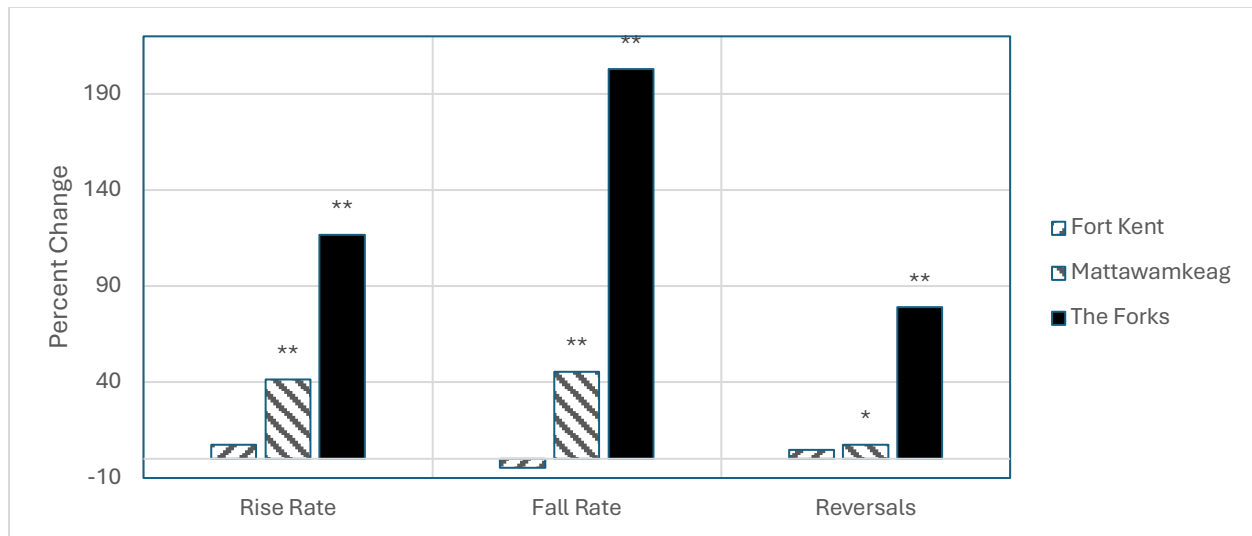


Figure 20. Change in rate and frequency of change in flow from before dam construction to after construction of the Harris Station Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

5.6 Median and Mean

There is significant change between pre-1952 and post-1954 conditions in annual median and mean at both of the reference gages and the downstream gages. There were significant increases in both mean and median at all three gages. Annual median increased by 31.9% at Fort Kent while annual mean increased by 16.9%. Annual median increased at Mattawamkeag by 30.0 %, and annual mean increased by 16.8%. At The Forks, the annual median increased by 18.1% and the annual mean increased by 14.4% (Fig. 21).

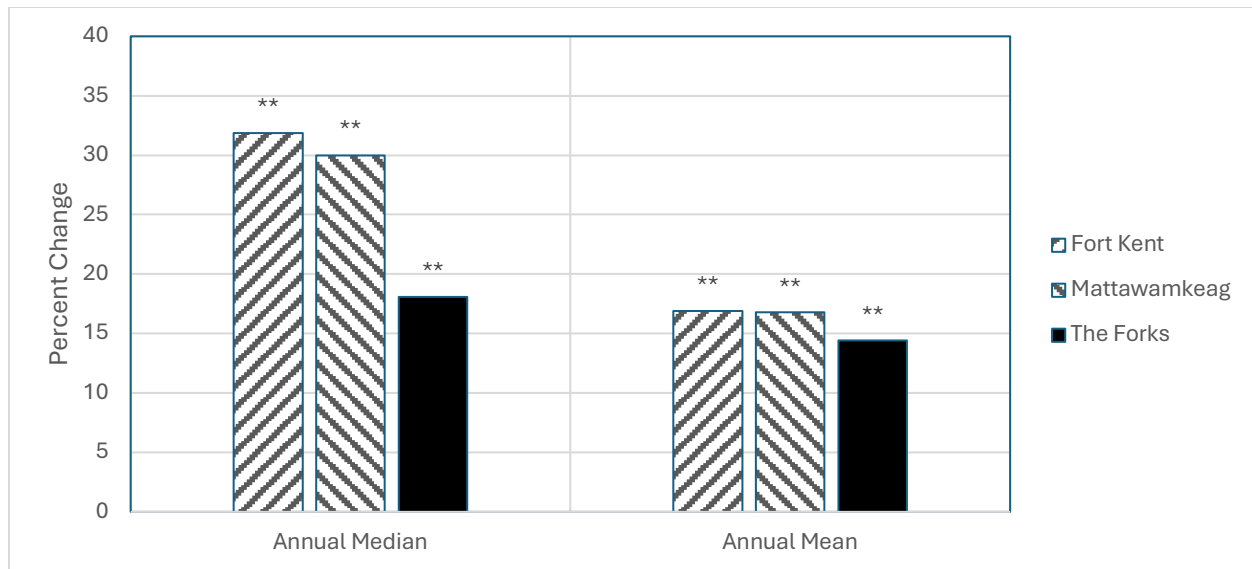


Figure 21. Change in annual median and mean flow from before dam construction to after construction of the Harris Station Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

5.7 Peak Flows and High Flows

There is significant change in high flow metrics from pre-1952 to post-1954 conditions at the reference gages and the downstream gage. The significant change in peak flow is at The Forks, which had a 20.4% increase in instantaneous peak flow. All three gages had an increase in the mean of the 10% of daily mean flow per year, ranging from 7.2% at Mattawamkeag to 11.6% at The Forks. There was also an increase in annual threshold for top 10% of daily mean flows at all three gages. This significant increase ranged from 8.0% at Fort Kent to 18.0% at The Forks (Fig. 22).

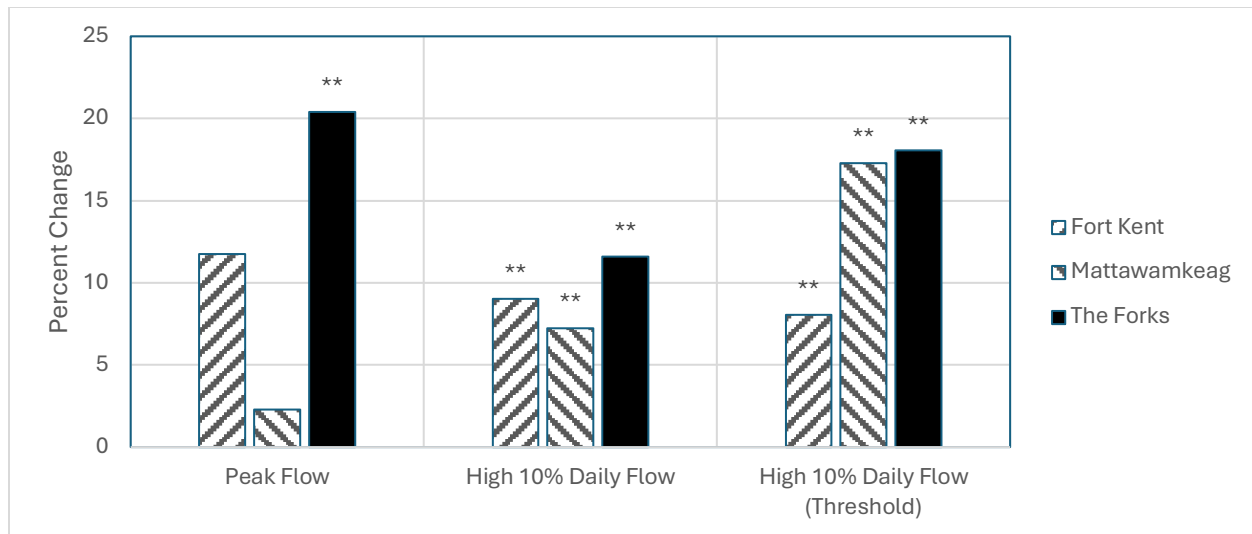


Figure 22. Change in annual instantaneous peak flow, mean of the highest 10% of daily flow annually, and the threshold for highest 10% of daily flow annually from before dam construction to after construction of the Harris Station Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

5.8 Geomorphology

There are no public field measurement data at both the reference gages and the gages downstream of the Harris Station Dam during pre-1952 and post-1954 time periods. This means that the geomorphology alteration of the Kennebec River due to Harris Station Dam cannot be evaluated by DAMS.

5.9 Sediment Mass Balance

All three gages being analyzed to measure alteration of the Kennebec River due to the construction of the Harris Station Dam do not collect sediment flow data. Due to the lack of data, the sediment mass balance of the Kennebec River cannot be evaluated by DAMS.

5.10 Flood Reduction Magnitude

The flood reduction magnitude was able to be calculated at both the reference gages and at the downstream gage for the Harris Station Dam. The reference gages had flood reduction

magnitude values ranging from 0.99 to 0.87. The flood reduction magnitude value at The Forks was 0.92 (Table 7).

Table 7. Flood magnitude reduction from before dam construction to after dam construction of the Buford Dam at stream gages upstream and downstream of the impoundment.

Gage	Flood Magnitude Reduction
Fort Kent	0.990498812
Mattawamkeag	0.870786517
The Forks	0.920634921

5.11 Precipitation

Generally, across all watersheds, there is an increase in precipitation from the pre-1952 time period to the post-1954 time period. This increase tends to be greater and be significant during the later summer and fall months. This increase tends to be smaller and less likely to be significant during the winter, spring, and early summer months. The only months that show a decrease in precipitation in the watershed from pre-dam to post-dam timer periods are all at the watershed above The Forks. These months are February, July, August, and December. Of these four months, February is the only non-significant decrease and a much smaller decrease than the other three (Fig. 23).

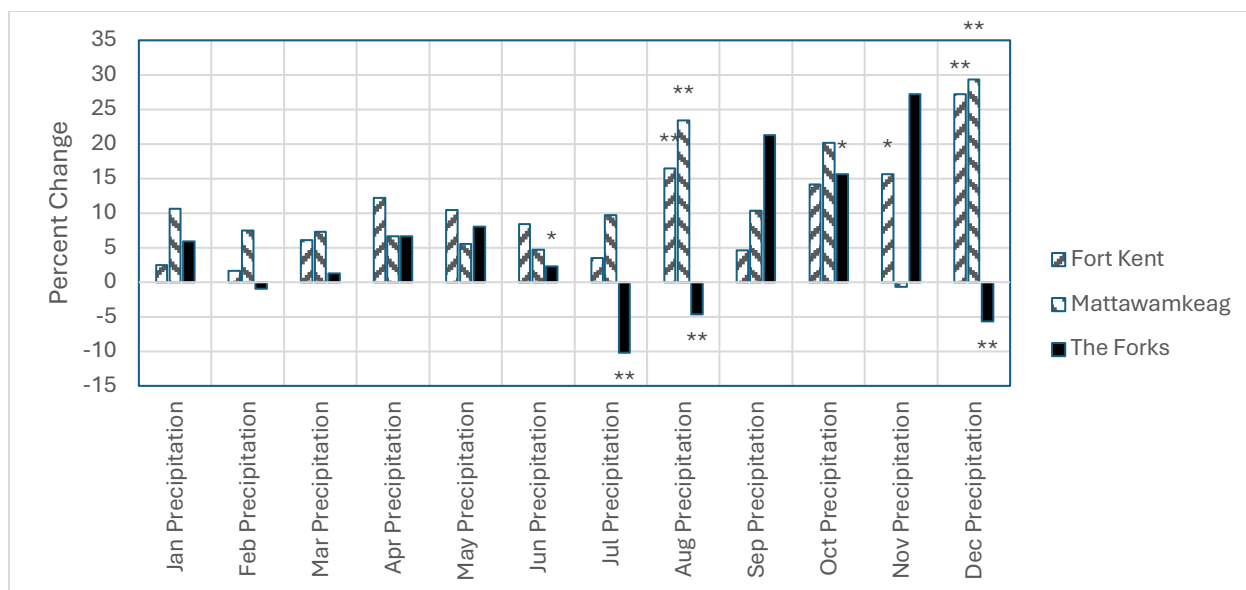


Figure 23. Change of monthly precipitation from before dam construction to after construction of the Buford Dam at stream gages upstream and downstream of the impoundment. $p < 0.1$ is represented by * and $p < 0.05$ is represented by **.

6. Discussion

The hydrologic and geomorphic alteration of the Chattahoochee River due to the Buford Dam and Kennebec River due to the Harris Station Dam is striking. Each river has responded uniquely to impoundment.

6.1 Buford Dam

6.1.1 Alteration of High, Medium, and Low Flow

The Buford Dam altered the high, medium, and low flows of the Chattahoochee River. Low flows are measured in IHA Group 2 and IHA Group 4. The low flow metrics in these groups show generally the Buford Dam decreased low flows but increased the number of low flows per year. This is evident when comparing upstream and downstream gages for the number of low pulses and 1-, 3-, 7-, 30-, and 90-day minimum flows. It is worth noting that the Norcross gage shows increases in minimum flows while the other downstream gages do not. This could be

attributed to the fact the Suwanee Creek meets with the Chattahoochee River upstream of the Norcross gage, affecting the Norcross gage.

The annual mean and median flows are a way to understand how medium flows have changed due to impoundment. The annual median and mean at the Dahlonge gage decrease slightly, but it is not a significant value. The annual median and mean at the Leaf gage increased, but this change is also not significant. Downstream of the Buford Dam, the annual median and mean decreased significantly at the Buford Dam gage, and the annual mean decreases significantly at the Buford gage. This means that a decrease in medium flow of the Chattahoochee River can be attributed to the construction of the Buford Dam.

Alteration in high flows is measured in DAMS through IHA group 2, IHA group 4, the peak and high flows, and flood magnitude reduction. The high flow results of IHA group 2, annual instantaneous peak flow, the mean top 10% of daily flow, and flood magnitude reduction values all give evidence that the Buford Dam decreased high flows on the Chattahoochee River. Each one of these metrics show a larger decrease in high flows at the downstream gages than any decrease in high flow at upstream gages, if there is an upstream decrease at all. This aligns with results from Williams and Wolman (1984), Magilligan and Nislow (2005), and Graf (2006). Of these three papers, Magilligan and Nislow (2005) were the only to publish the percent change in high flows due the construction of the Buford Dam. Across the high flow metrics that are shared between Magilligan and Nislow (2005) and DAMS, there was a greater decrease in high flows in the percent change from pre-dam to post-dam in DAMS. Magilligan and Nislow (2005) report a 64% decrease between pre-dam and post-dam conditions in 1-day maximum flow while DAMS reports a 65% - 72% decrease in the same metric over the three gages included. A similar

magnitude in difference of change is shown in the 3- and 7-day maximum flows. This shows that the Buford Dam has continued to decrease high flows in the last 20 years.

6.1.2 Alteration of Seasonality of Flow

DAMS records the seasonality of flows through IHA Groups 1 and 3. At the upstream Chattahoochee River gages, none of the changes in mean or median of mean daily flows between pre- and post-dam construction are significant for any month of the year. However, downstream of the dam, winter flows decrease significantly, and later summer/fall flows increase. This aligns with the results from Magilligan and Nislow (2005). Because northern Georgia does not receive any significant snow, the winter is when the highest flows normally are, and summer is the time when flows are lower. However, the dam evens out the flow throughout the year. This can be seen in the mean Julian day of the highest and lowest daily flow. The mean Julian day of the maximum daily flow at the Buford Dam and Buford gage occurred in the middle of January before dam construction but shifts to later in the winter after dam construction. The mean Julian day of minimum flow at the Buford Dam and Buford gage shift from the late fall to the middle or end of winter. There is minimal change at the upstream gages.

6.1.3 Alteration of Geomorphology

There is a decrease in MSBE at two gages downstream of the Buford Dam and at one of the two upstream gages. The gage with significant decrease downstream of the Buford Dam had a greater decrease in MSBE than the gage that had a decrease in MSBE upstream of the dam. These results agree with the MSBE changes reported in Williams and Wolman (1984). They found that there was decrease in MSBE above and below the Buford Dam, but the decrease in MSBE above the dam was less than the decrease below the dam. The decrease in MSBE reported

in Williams and Wolman (1984) and by DAMS are in agreement, both suggesting that the construction of the Buford Dam has caused degradation downstream of the Buford Dam.

Channel capacity and mean depth of the Chattahoochee River also decreased downstream of the Buford Dam but increased upstream of the dam. This is despite of degradation downstream of the dam. Because channel capacity and mean depth is related to both geomorphology and hydrology, this decrease might be a hydrologic signal related to decreased high flows. This decrease in channel capacity is still important to note because alteration in channel capacity is an important factor in fluvial flood hazard risks (Slater et al., 2015).

6.2 Harris Station Dam

6.2.1 Alteration of High, Medium and Low Flow

There has been alteration to low flows on the Kennebec River since the construction of Harris Station Dam. There has been a significant increase in downstream gages in all low flow metrics except for the 1-day minimum flow. A similar pattern can be seen at either one or both of the reference gages, evidence that this is a signal of the general increase in precipitation seen at all watersheds above the stream gages rather than solely due to changes in low flow as described in previous studies (Graf, 2006; Magilligan & Nislow, 2005; Williams & Wolman, 1984). The increase in low flow at the downstream gage could be attributed to both the construction of the Harris Station Dam and increased precipitation.

There is also a change in annual median and mean flow of the Kennebec River that can be attributed to the construction of the Harris Station Dam. The annual median and annual mean all increase for both the reference gages and the downstream gage. However, the increase in annual means is almost two times larger at the reference gages than the downstream gage. This

means that despite a general increase in medium flow, the construction of the Harris Station Dam led to a smaller increase in medium flow. This smaller increase in medium flows downstream of the Harris Station Dam compared to the unimpounded rivers in the region indicate that the Harris Station Dam is buffering the effects of changes in precipitation associated with climate change.

The high flows of metrics of all gages associated with the Harris Station Dam indicate an increase in the high flows across the region. While the increase in high flows downstream of a large impoundment dam is in contrast to the results of many of the studies that examine how a large number of rivers were affected by impoundment (Graf, 2006; Magilligan & Nislow, 2005; Williams & Wolman, 1984), the magnitude of increase in high flows is lesser downstream of the Harris Station Dam than on other unimpounded rivers in the region. This is further evidence to suggest that the Harris Station Dam is buffering the effects of climate change of streamflow in the Kennebec River compared to other rivers in the region.

The increase in low, medium, and high flows downstream of the Kennebec is part of a larger story of increasing flow in rivers in the region associated with precipitation increases. The Harris Station Dam is mitigating some of this climate change associated increase. However, as Williams and Wolman (1984) reported, stream flow through a dam is controlled almost by the release schedule of the dam. It is worth considering that one of the reasons for the increase in streamflow downstream of the Harris Station Dam is because Harris Station Dam releases high flows intermittently for white water conditions on the Kennebec River (SafeWaters by Brookfield Renewable, 2025). The influence commercial rafting interests have on the release schedule is substantial and should not be overlooked.

6.2.2 Alteration of Seasonality of Flow

Across both the reference gages and downstream gages, there is an increase in flow across the late summer, fall, winter, and early spring months. This change from pre-dam to post-dam patterns in seasonal flow could be attributed to warmer winter weather due to climate change causing more snow to melt throughout the winter and the increase in late summer precipitation and fall precipitation.

There is a greater increase or consistent increase from pre-1952 to post-1954 in precipitation at the watershed above downstream gage compared to the watersheds above the reference gages in September to October. However, the increase in streamflow during these months from pre-1952 to post-1954 is much less at the downstream gage compared to the upstream gage. This is further evidence that despite an increase in precipitation, the Harris Station Dam is acting as a buffer against the effects of climate change on the Kennebec River.

6.2.3 Alteration of Geomorphology

There is no data that DAMS can access that is used to calculate a metric to measure geomorphic change. Additionally, sediment data is not collected and published. This means that DAMS cannot calculate the potential change that the Harris Station Dam had on the Kennebec River.

7. Implications

As we reach the quarter point of the 21st century, and dams continue to be built around the world, it remains important to understand how impounding rivers affect the hydrology and geomorphology of the river downstream of the impoundment. DAMS allows for straightforward and fairly comprehensive monitoring of this change. DAMS allowed me to show that both the

Buford Dam on Chattahoochee River and the Harris Station Dam on the Kennebec River are regulating flow on their respective rivers, causing a decrease in flow or smaller increase in flow compared to their ungauged counterparts.

Despite the strength of DAMS, it is not without its faults. To comprehensively measure how an impoundment alters a river, there must be a USGS stream gage downstream of the dam and another stream gage that can act as a baseline, either upstream of the impoundment or sitting on a similar but free flowing river. While the network of USGS is vast, containing 8,705 stream gages that record at least gage height and stream flow as of October 2024 (Water Resources Mission Area, n.d.), there are many more ungaged rivers in the United States than there are gaged ones. The lack of gauging means hydrologic and geomorphic alteration of these rivers, regardless of the source of the alteration, is far more difficult to measure. It certainly means that DAMS cannot be run on it. Increasing the number of rivers that are gaged will allow us to know more about the state of the rivers in the United States and how they change over time and space.

Sediment monitoring – both bed load and suspended load – pales in comparison to the stream flow monitoring that is comprehensive in comparison. Fewer rivers in the United States have continuous sediment monitoring than have continuous stream flow monitoring. All eight stream gages examined to measure hydrologic and geomorphic change using DAMS in this study did not have continuous sediment monitoring. Some had singular periods of a day where bed load or suspended load was measured, but none had the long-term monitoring needed to measure how impoundment has altered the sediment mass balance of the rivers. An increase in the monitoring of bed load and suspended load sediment is vital as our rivers continue to change due to impoundment and climate change. Knowledge of how sediment flux is changing due to impoundment is vital because fluvial sediment transport is crucial to the health of both rivers and

coastal environments (Dai et al., 2008). It is currently unknown how sediments fluxes on American rivers are changing over time and space, or whether they are changing at all.

Because DAMS is open-source and built in R, theoretically it can be adapted to other stream gauging networks outside of the USGS network that might collect similar data but format it differently or have different means of access. This means that DAMS could be applied to rivers outside of the United States, allowing potential users to understand how both the hydrology and geomorphology of rivers have been altered. This is important as dams throughout the world age and more dams are built, especially in developing economies (Zhang & Gu, 2023). While DAMS is practical in theory, there are many barriers to applying DAMS throughout the world outside of current data access issues for the program. The largest barrier to the application of DAMS outside of the United States is the current geographic bias in the distribution of stream gages (Fig. 24) (Krabbenhoft et al., 2022). Generally, North America, Europe, and parts of Asia have robust stream gage networks while there is a lack of stream gage coverage in most parts of South America, Africa, Australia, and Central Asia. This means that despite the fact that the majority of recent large impoundments have been built in Africa, Asia, and South America (Fig. 1), the pre-dam geomorphology and hydrology of the rivers they impound might not fully be known or publicly available.

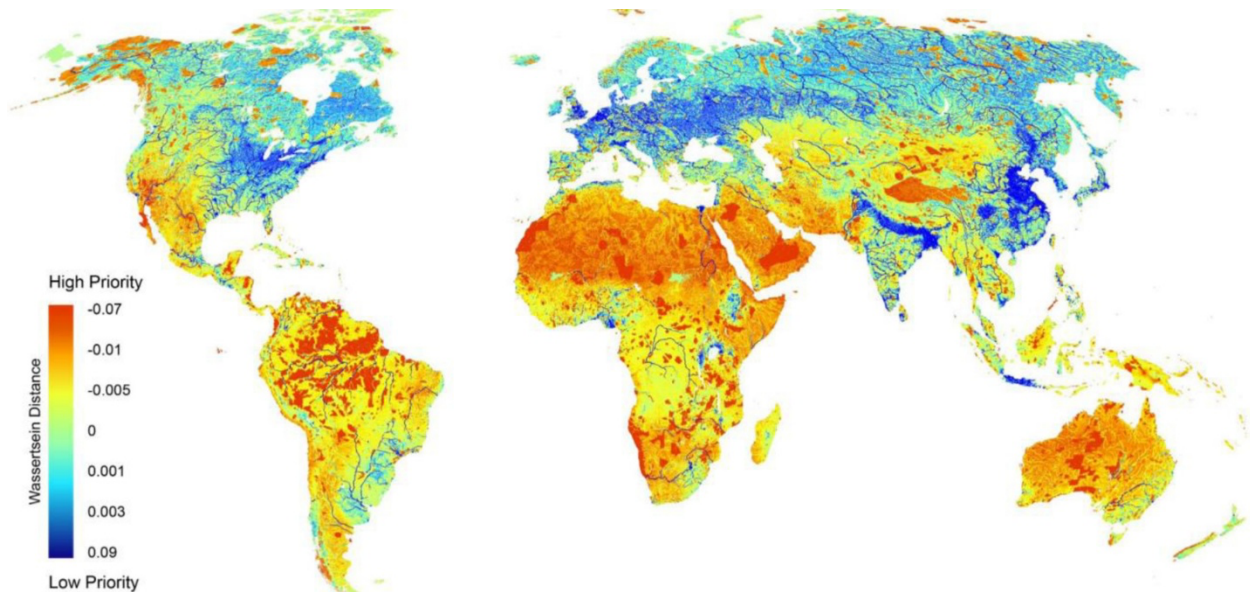


Figure 24. Map showing bias in stream gage locations globally. Red denotes areas that would be high priority for the installation of new gages to reduce bias while blue areas denote the opposite. From Krabbenhoft et al., 2022

The modular nature of DAMS means its use case can extend beyond measuring geomorphic and hydrologic change in a river due to impoundment. DAMS can be applied to any USGS gaged river. Additionally, as it is relatively straightforward to use and requires none to minimal knowledge of how to use R, its potential user base is greater than those with proficiency in R. The potential user base includes environmental non-profits, researchers, and classrooms. As large dams around the world get older, it is important to understand how dams affect both the geomorphology and hydrology of the rivers they impound, and DAMS is a tool that can be used potentially by many to help monitor the world's changing rivers.

8. Appendix

Appendix A. Full description of all metrics included in DAMS.

Metric	Description
Mean or median value for each calendar month	Mean or median of mean daily flows for each month of the calendar year
Annual minimum 1-day mean	Minimum single day mean flow during a calendar year
Annual minimum 3-day mean	Minimum mean flow of all rolling 3-day means of daily mean flow during a calendar year
Annual minimum 7-day mean	Minimum mean flow of all rolling 7-day means of daily mean flow during a calendar year
Annual minimum 30-day mean	Minimum mean flow of all rolling 30-day means of daily mean flow during a calendar year
Annual minimum 90-day mean	Minimum mean flow of all rolling 90-day means of daily mean flow during a calendar year
Annual maximum 1-day mean	Maximum single day mean flow during a calendar year
Annual maximum 3-day mean	Maximum mean flow of all rolling 3-day means of daily mean flow during a calendar year
Annual maximum 7-day mean	Maximum mean flow of all rolling 7-day means of daily mean flow during a calendar year
Annual maximum 30-day mean	Maximum mean flow of all rolling 30-day means of daily mean flow during a calendar year
Annual maximum 90-day mean	Maximum mean flow of all rolling 90-day means of daily mean flow during a calendar year
Zero flow days annually	Number of days per calendar year where the stream has no flow
Julian day of annual 1 day maximum	Julian day of the year of annual maximum 1-day mean
Julian day of annual 1 day minimum	Julian day of the year of annual minimum 1-day mean
Number of high pulses per year	Number of periods where the mean daily stream flow is in the top 25% of daily stream flow per calendar year. A period is any continuous number of days.

Number of low pulses per year	Number of periods where the mean daily stream flow is in the bottom 25% of daily stream flow per year. A period is any continuous number of days.
Mean duration of high pulses each year	The mean duration of days of each period where the daily stream flow is in the top 25% of daily stream flows during the calendar year.
Mean duration of low pulses each year	The mean duration of days of each period where the daily stream flow is in the bottom 25% of daily stream flows during the calendar year.
Means of all positive differences between each consecutive daily means	Mean of all increases in mean daily stream flow from day to day during a calendar year
Means of all negative differences between consecutive daily means	Mean of all decreases in mean daily stream flow from day to day during a calendar year
Flow reversals	Number of changes between increasing and decreasing daily mean stream flow
Annual median	Annual median of daily mean flows
Annual mean	Annual mean of daily mean flows
Instantaneous peak flow	Stream flow during the instant of peak stream flow during the year
Flood Frequency Series	Shows the instantaneous peak flow at different recurrence intervals
Annual Top 10% Flow	Top 10% of daily mean flows per year
Stream Width	Width of stream at stream gage
Stream Depth	Mean depth of the stream at stream gage
Channel Capacity	Cross sectional area of stream at stream gage
Mean Stream Bed Elevation (MSBE)	Mean elevation of the stream bed at the stream gage
Sediment Mass Balance	Ratio of pre-dam to post-dam sediment flux estimate derived from Lane's Balance
Flood Magnitude Reduction	Ratio of pre-dam to post-dam flood at two-year recurrence interval

9. References

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