Climatic Trend Impact on Alaskan Stream Discharge

https://github.com/wgrimshaw/Alaska_DBPs.git

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1 Rationale and Research Questions

1.1 Background

The climate is changing, in large part due to anthropogenic carbon emissions. These changes have different magnitudes around the world and local impacts of climate change vary as well. Specifically, climate change is already having greater impacts near the poles than many other parts of the globe, a process known as polar amplification or arctic amplification (Serreze et al 2009). Understanding how climate change is affecting discharge, especially in Alaska, has implications for water management, ecological processes, and the larger global system (if we consider ice-albedo feedback) (Kashiwase et al, 2017). Many communities rely on a given amount of water from snowmelt to arrive at certain times of the year, so a shift in the quantity or timing of discharge could drastically affect downstream users and water managers (Earth System Research Laboratory, 2017). Additionally, changing the amount of flow in rivers could affect sensitive biological communities (U.S. Geologic Survey). Furthermore, changes in temperature that result in glacial or permafrost melting could reduce the amount of reflective land cover, thus disrupting larger climate systems.

1.2 Research Question

To what degree does climate change affect discharge in Alaskan streams and rivers?

This guiding question encompasses three hypotheses:
1) Streams at varying latitudes will have different responses to changing climate with a monotonic trend related to latitude.

2) If streams are in areas that experience greater mean air temperature increases, then they will have greater discharge.

3) If temperature increases over time, the day of year of first snowmelt will occur earlier.

This study first seeks to examine if the magnitude of temperature changes over time increase with increasing latitude in Alaska. By analyzing historical streamflow records, we will investigate whether the magnitude of maximum daily temperature change causes a proportional change in the magnitude and timing of peak streamflow.

Another aspect of climate change's impacts on streamflow is the potential of melting permafrost or glaciers. This analysis uses cumulative annual streamflow and cumulative annual precipitation to determine if interannual snowpack is melting with increasing average temperatures. If so, we expect the difference between annual precipitation and annual streamflow to increase over time.

2 Dataset Information

2.1 Discharge

Discharge data were collected from the National Water Information System (NWIS) using the Data Retrieval package in R. The state of Alaska was divided into 10 bins of equal latitude, and daily discharge data was downloaded for the site in each latitude bin with the greatest number of samples. This dataset includes the site location, daily discharge, and county of the site, among other variables not used in the analysis.

Site information for each discharge site was also collected using the Data Retrieval package. Site information used in the analyses included upstream catchment area.

2.2 Temperature and Precipitation

Temperature and precipitation data were downloaded from the National Oceanic and Atmospheric Administration (NOAA) Climate Data Online web portal. As discharge stations do not collect data on temperature and precipitation, the climate data for each latitude bin were downloaded from a station in the same county as each selected discharge station. Though counties in Alaska are large, this was the most reliable way to find climate stations near the discharge stations. In each county, daily precipitation, maximum temperature, and minimum temperature, data were downloaded from one station. The criteria for station selection include data extending to the current date, beginning at the earliest date, with at least 80% data coverage. This dataset also includes site location. All site locations are visible in Figure XXX.

3 Data Wrangling

Variable	Units (if known)	Type of Variable	Hypothesis
Discharge	Cubic feet per second	Response	1a, 1b, 1c
Site Number	Latitude/Longitude	Predictor	1a
Date Time	Year/Month/Day	Predictor	1c
Date of First Snowmelt	Year/Month/Day	Predictor	1a, 1b, 1c
Air Temperature	Celsius	Predictor	1b
Precipitation	Millimeters	Predictor	1a, 1c
HUC 8 Watershed Size	Square Meters	Predictor	1a, 1b
Permafrost Melt	Qualitative	Predictor	1b
Glacial Coverage/Melting	Qualitative	Predictor	1b

3.1 Importing, Cleaning, and Addressing Date Issues

The state of Alaska was divided into 10 bins of equal latitude. Precipitation and temperature data for 10 Alaskan NOAA stations-one inside each latitude bin-was obtained from NOAA's Climate Data Online web portal, and discharge data was retrieved from NWIS's Data Retrieval package using one site in each latitude bin with the greatest number of samples. All discharge data resided in one CSV entitled NWIS_Discharge. All raw CSVs were imported into our Raw Data folder within our project repository on Github, and imported into R using the read.csv function.

Each of the 10 NOAA stations classified by latitude bin had a unique CSV that was cleaned prior to joining. Ancillary columns from each of the 10 dataframes were removed in order to ensure that each CSV had the same columns in the same order. In order to address date-time issues in the NOAA CSVs for Bin 1 and Bin 5, the as.DATE function was used to change the "DATE" column fron a factor to a date, in the format month/day/year. Next, we changed the format of the "DATE" column to a two digit year, a two digit month, and the two digit day. A function was then written to create early dates that had been misrepresented as years after 2019. Then, the DATE column was inserted into the function written above for each row of the DATE column. Finally, the as.DATE function was used to convert the DATE column into a 4 digit year, a two digit month, and 2 digit day format, our preferred format.

3.2 Joining Data

After all 10 NOAA dataframes containing precipitation and temperature data were cleaned, they were all joined by row using the rbind function into a new CSV entitiled "TempPrecip". Next, the "site_no" column in the NWIS_Discharge dataframe was converted into a factor using the as.factor function. The revalue function within the "plyr" package was then used to create a new "Bin" column renaming the USGS Station Numbers in the "site_no" column by their bin number. The "Date" column in the Discharge dataframe was renamed to "DATE" so that it matched the "DATE" column in the "TempPrecip" dataframe. Finally, the merge function was used to join the "TempPrecip" and "NWIS_Discharge" dataframes by "DATE" and "Bin" into a new CSV entitled "AlaskaTempPrecipDischarge", and cleaned for clarity.

4 Exploratory Analysis

4.1 Site Locations

```
## Reading layer `cb_2018_us_state_20m' from data source `C:\Users\walke\OneDrive\Docume
## Simple feature collection with 52 features and 9 fields
## geometry type:  MULTIPOLYGON
## dimension:      XY
## bbox:           xmin: -179.1743 ymin: 17.91377 xmax: 179.7739 ymax: 71.35256
## epsg (SRID):    4269
## proj4string:    +proj=longlat +datum=NAD83 +no_defs
```

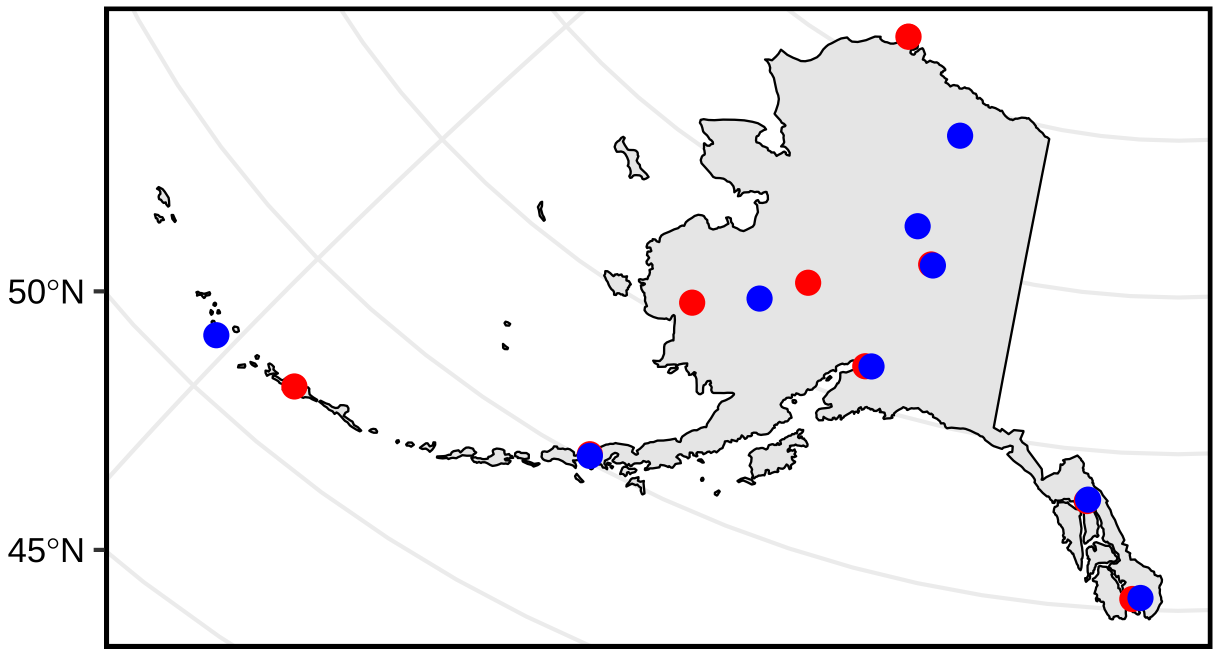


Figure 1: Map of Site Locations. The red sites are NOAA stations, while the blue sites are the NWIS Stations. There is one NOAA station and one NWIS station per latitude bin. Each pair of stations are located in the same county.

4.2 Temperature

Though climate change is a complex process, the easiest parameter to estimate the magnitude of climate change is temperature. Figure 2 shows the maximum daily temperature for the nine NOAA sites over each site's period of record. As expected, the range of maximum temperature increases with increasing latitude. Besides site one, all other sites have reasonable overlap in their periods of record and at least cover from 1980 to 2018. There are gaps in the records of multiple sites that require interpolation however. Larger gaps, such as the 1990s gap for site two and the gaps before 1950 for site three, are not filled in this analysis, and instead the earlier time periods are left out of the time series analysis. Shorter data gaps are filled. No obvious temperature trends can be seen in the records of any sites.

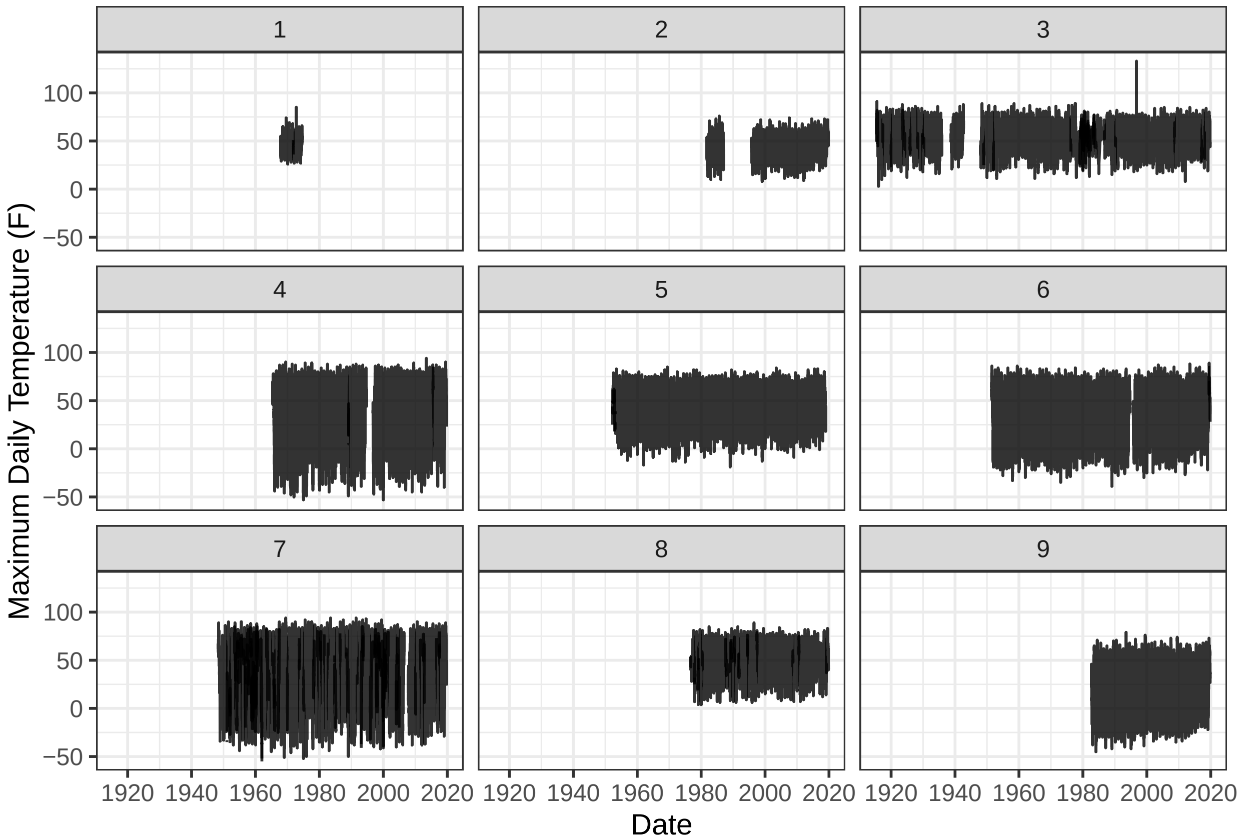


Figure 2: Maximum daily temperature records of the nine climate sites, showing variation in period of record, continuity of the record, and temperature range.

4.3 Snowmelt

Recognizing climate change can affect conditions which dictate the timing of snowmelt, we chose to investigate whether timing was in fact changing over time. In order to minimize inconsistencies in period of records for the data across various latitude bins, discharge was used as a proxy for changes in snowmelt. Figure 3 shows day of year versus mean discharge for all latitude bins. Figure 4 is similar to Figure 3 but excludes latitude bins 6 and 8, in order to better visualize how mean discharge changed throughout the year on average for the other latitudes. These graphs were made to provide insight into the variability of when snowmelt had been occuring at the various latitude bins.

Graphs exploring day of year compared to discharge were for all latitude bins. Figure 5 shows day of year compared to discharge for only latitude bin 6. This latitude bin was of interest as it exhibited the trend we expected, a spike in discharge occurring sooner for years later in the period of record. Even when looking at only six years at a time, as seen in Figure 6, the same trend is clear.

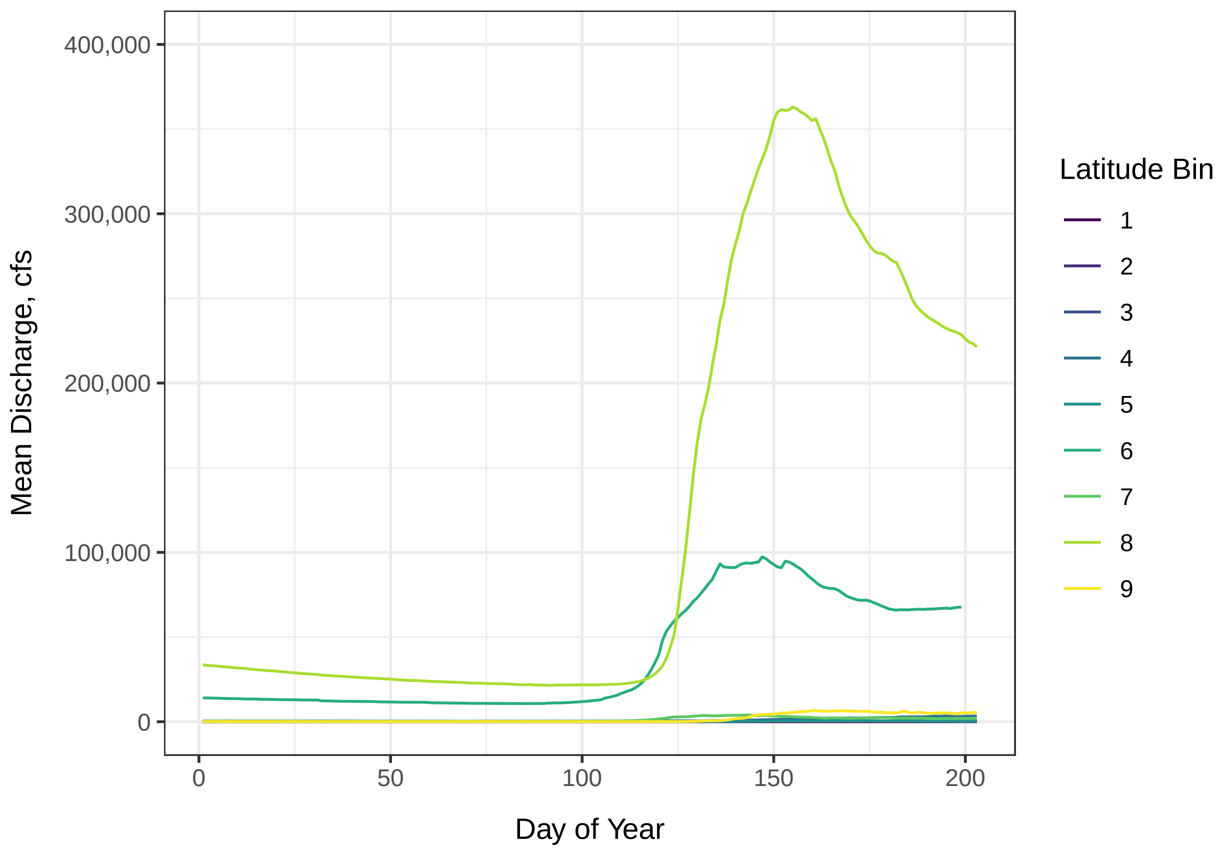


Figure 3: Day of Year vs. Mean Discharge. This figure shows mean discharge across all nine latitude bins for each day of the year. This graph served to illustrate variation across sites as to when first day of snowmelt and peak snowmelt would occur.

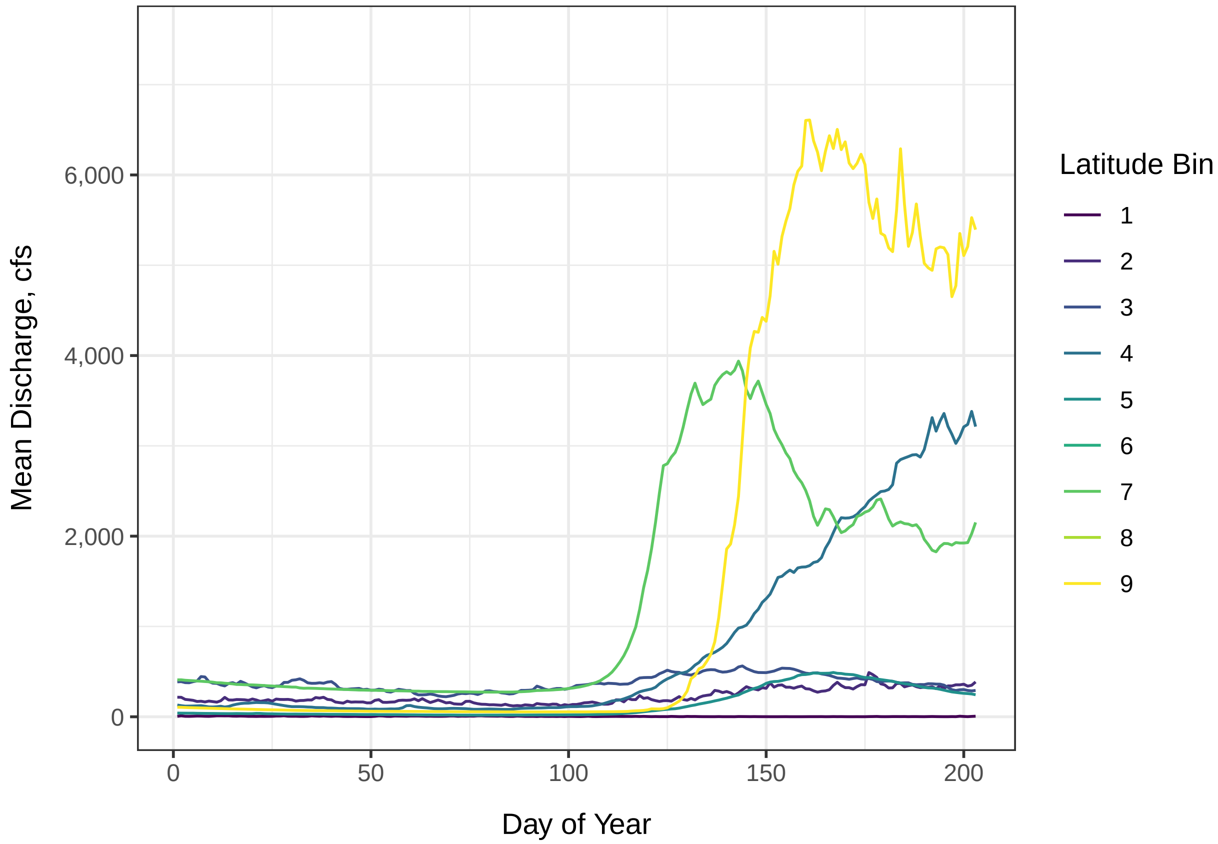


Figure 4: Day of Year vs. Mean Discharge for all bins besides 6 and 8 in order to show variations in site with lower discharge.

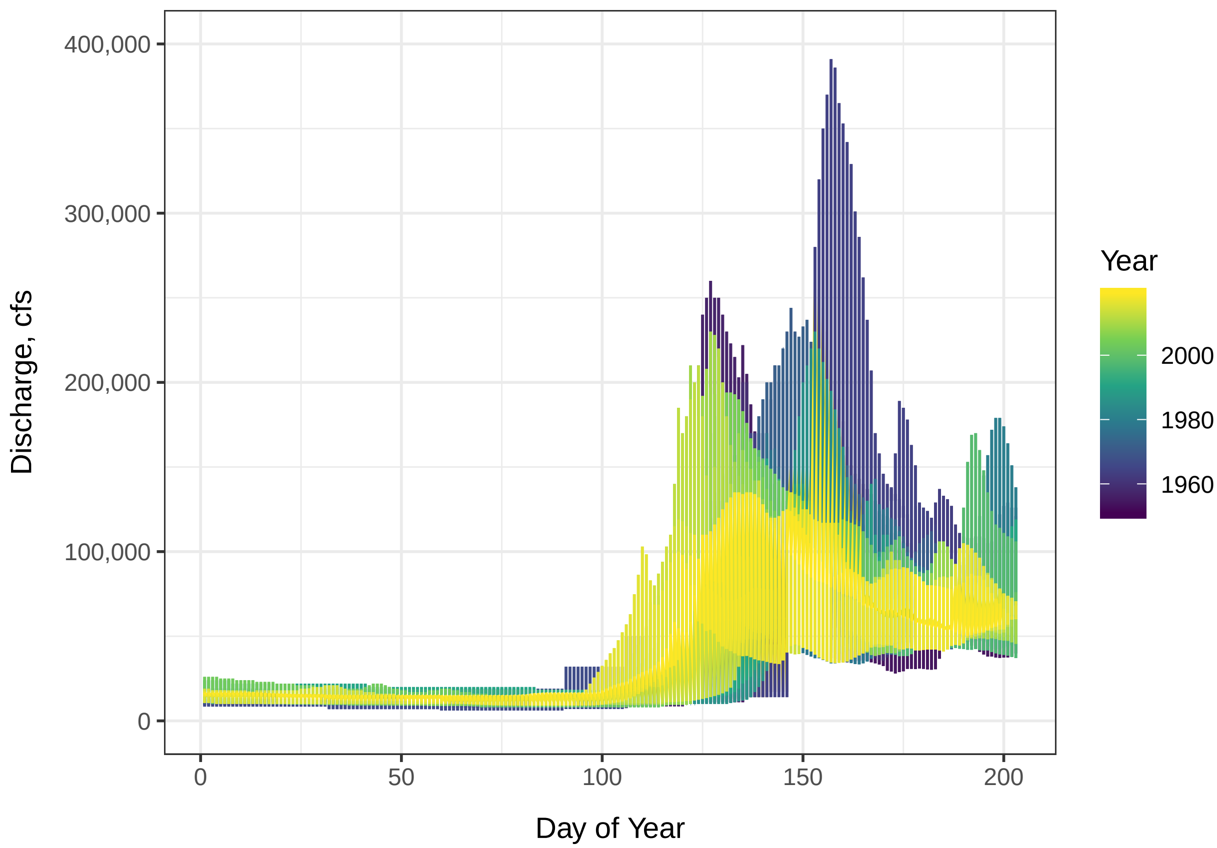


Figure 5: Day of Year vs. Discharge. This figure shows how discharge changes with day of year across the entire period of record for Bin 6. This provided a visual cue as to whether snowmelt was occuring earlier and during what time of the year the shift was occuring.

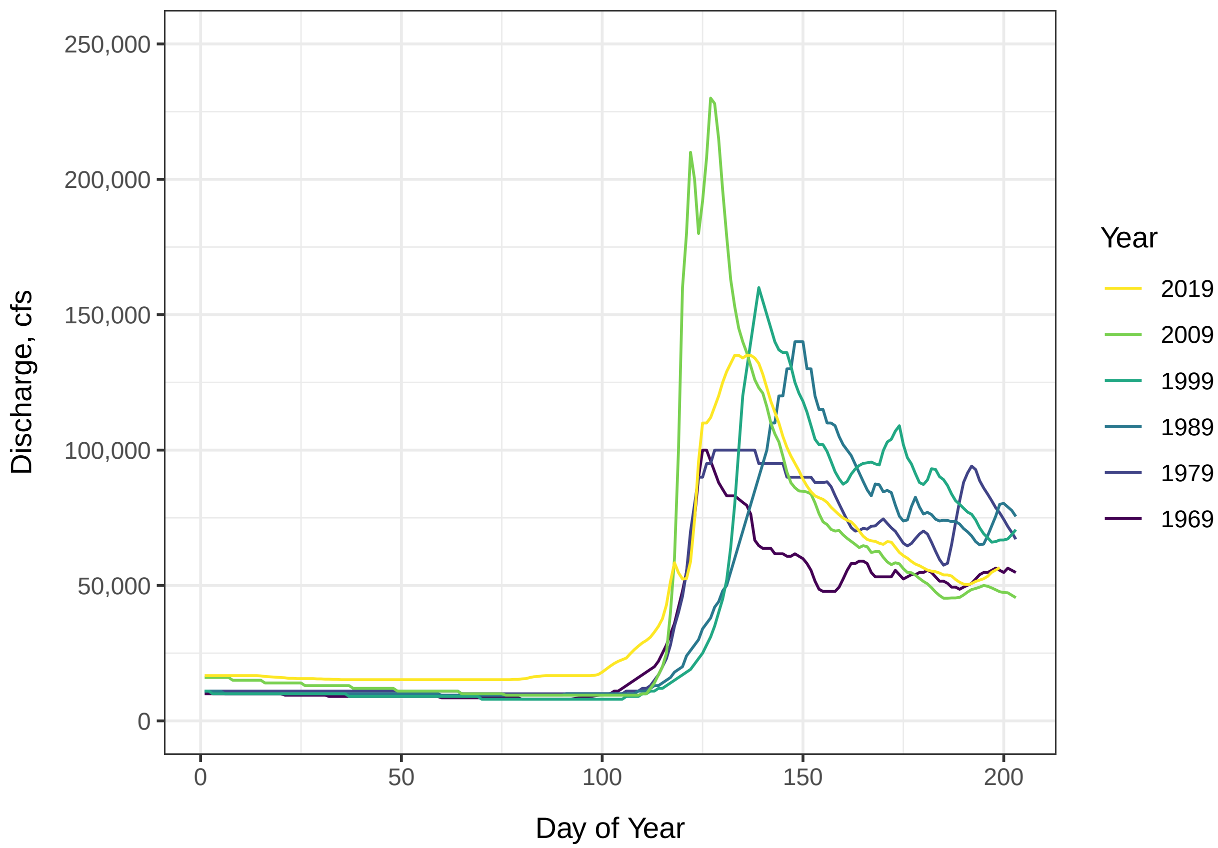


Figure 6: Day of Year vs Discharge. This figure shows how discharge changes with day of year every ten years across the period of record for fifty years. This provided a visual cue as to whether snowmelt was occuring earlier and during what time of the year the shift was occuring.

4.4 Precipitation

While there are significant regional and seasonal differences in precipitation changes, the mean annual precipitation across the United States has increased about 4% from the 1901-2015 period of record (Walsh et al. 2014). Long-term station observations from core climate networks served as a primary source to establish observed changes in precipitation. Alaska shows little change in annual precipitation (+1.5%); however, in all seasons, central Alaska shows declines and the panhandle shows increase (Easterling et al., 2017).

Figure 7 shows precipitation over each of the nine NOAA site's period of record, colored by bin. As expected, Bin 3 clearly has the largest range in the magnitude of precipitation, and precipitation in Alaska appears to decrease with increasing latitude.

This is substantiated by the fact that currently dry regions in Alaska are projected to become drier due to accelerated evaporation caused by warmer temperatures and longer growing seasons, while wet areas are projected to become wetter (EPA, 2017). Bin 3's station is located in Ketchikan, Alaska, which has a temperate oceanic climate and is dubbed the "rainfall capital of Alaska". There are 2 main data gaps in the precipitation period of record. One large gap occurs from the mid to late 1930s, presumably due to the Great Depression, and the second large gap occurs from August 31, 1942 to January 1st, 1948, presumably due to the second World War. These two gaps are not filled in this analysis.

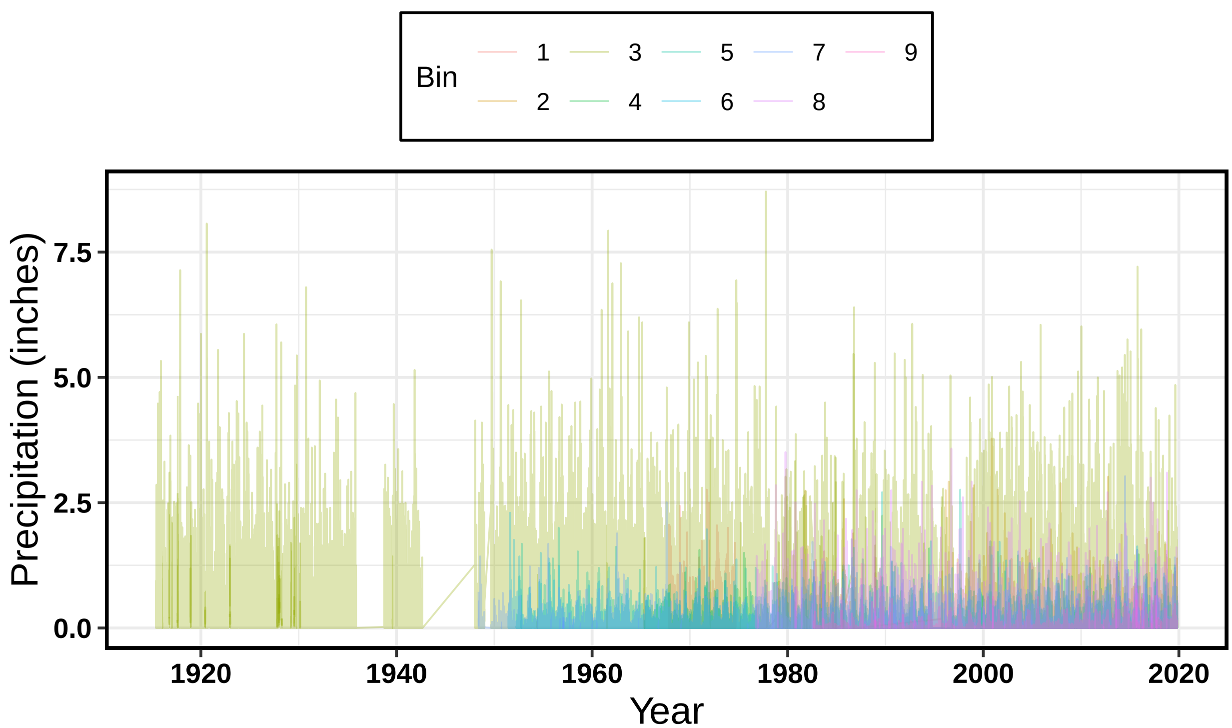


Figure 7: Precipitation Measured Over the Entire Period of Record by Bin. This figure shows the general pattern of precipitation changes over time, differentiated by the latitude bin (color). Bin 3 has the most sample points for the entire precipitation period of record. Bin 3's precipitation range has the greatest magnitude compared to the other bins.

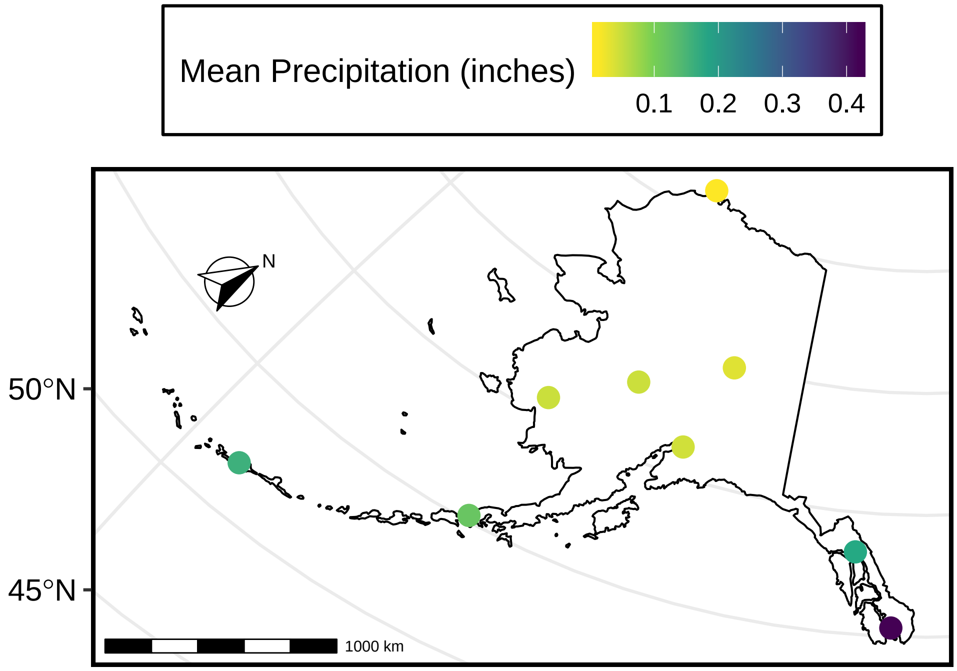


Figure 8: Map of Mean Precipitation across Alaska by Bin. This map depicts Bin 3 as having the highest mean precipitation across the state, with the lowest mean precipitation falling in northernmost Bin 9.

4.5 Discharge

To analyze the seasonal change of discharge, it is helpful to know the general trend of discharge over time. Figure 9 shows the discharge of 9 bins over time. From this graph, it is clear to see that Bin 6 and 8 have 2 largest river and they also have obvious seasonal changes. Trend of discharge of other bins cannot be identify right now and need further analysis.

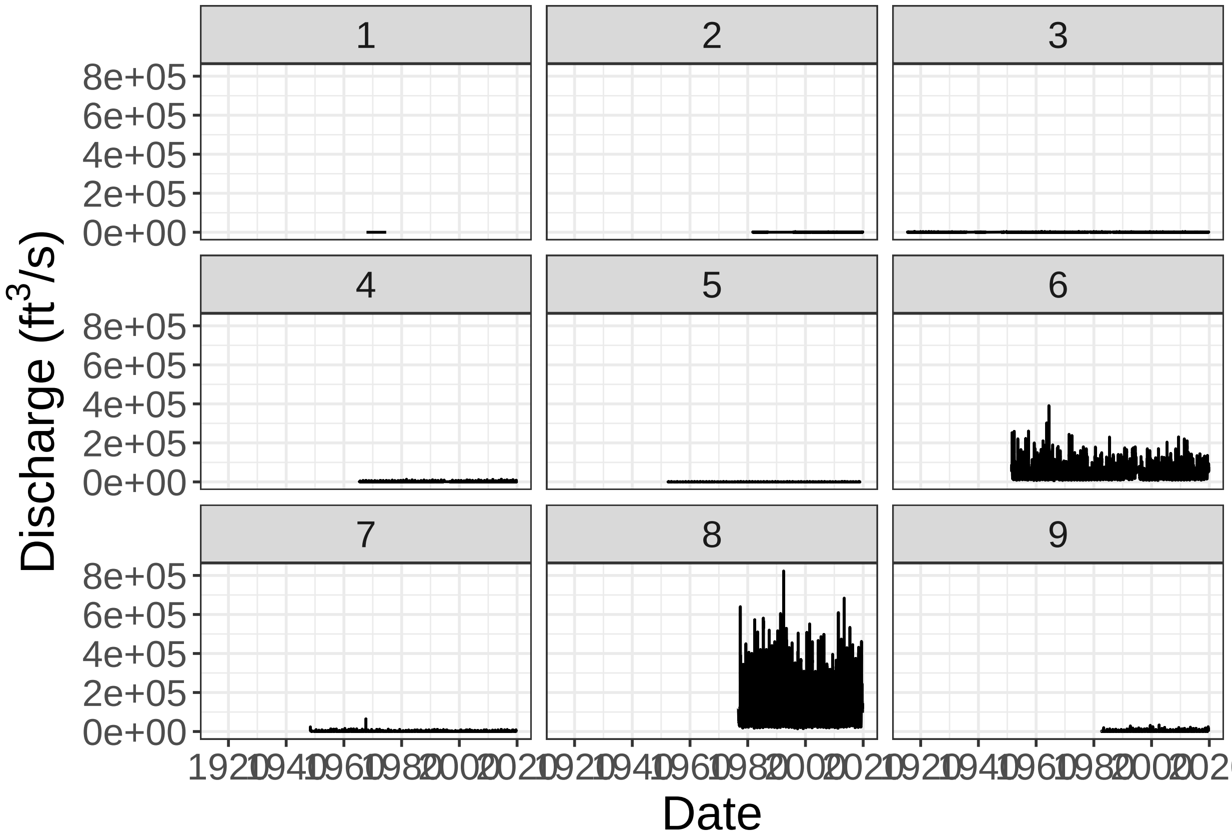


Figure 9: Discharge records for all nine bins.

5 Analysis

5.1 Temperature

For each latitude bin, the monthly average maximum temperature was calculated from the daily temperature data. As previously mentioned, the earlier data for sites two and three were discarded and not used for analysis. All other data gaps of at least one year in length were filled using the average maximum temperature for each month over the period of record for each site. However, if there were shorter data gaps of less than one year in length, monthly maximum temperatures were filled using linear interpolation from the nearest neighbor points.

For each latitude bin, a Seasonal Mann-Kendall test was performed on the monthly time series to determine if there had been a change in temperature over the period of record and the directionality of the trend. The Seasonal Mann-Kendall was also used to determine which individual months had statistically significant temperature trends and the directionality of those trends. If there was a statistically significant trend over the period of record, the seasonal sen's slope test was used to determine the average magnitude of the change.

Figure 10 shows the monthly average maximum temperature for site 5, near Anchorage, over time. The monthly average maximum temperature had a statistically significant trend (Seasonal Mann-Kendall, $z=4.87$, $p<0.001$). The blue line shows the magnitude of this trend as calculated by the seasonal sen's slope, indicating a 0.04 degree fahrenheit annual increase in average maximum temperature. It should be noted that the statistical tests used here do not estimate the intercept of the seasonal trend line, so while the figure shows the average seasonal temperature increase, the location of the intercept is only an approximation to assist the visualization.

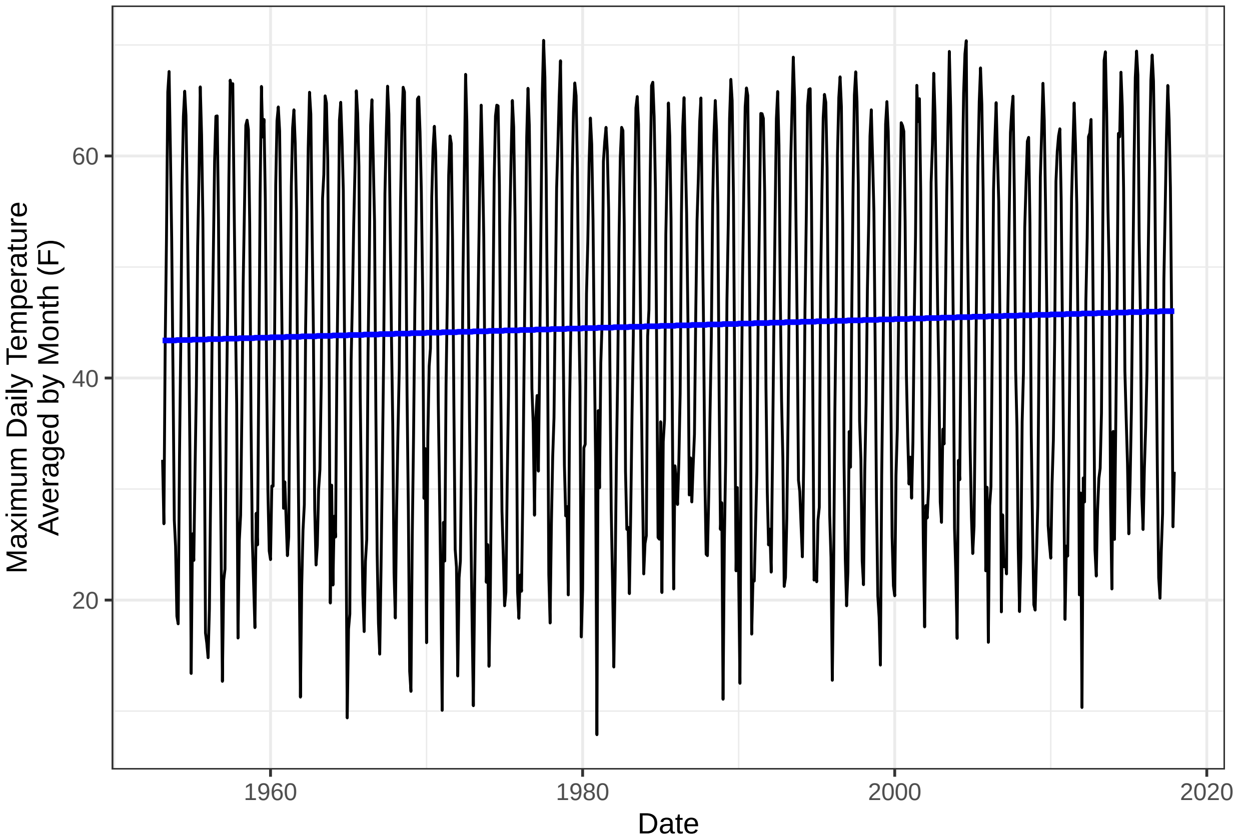
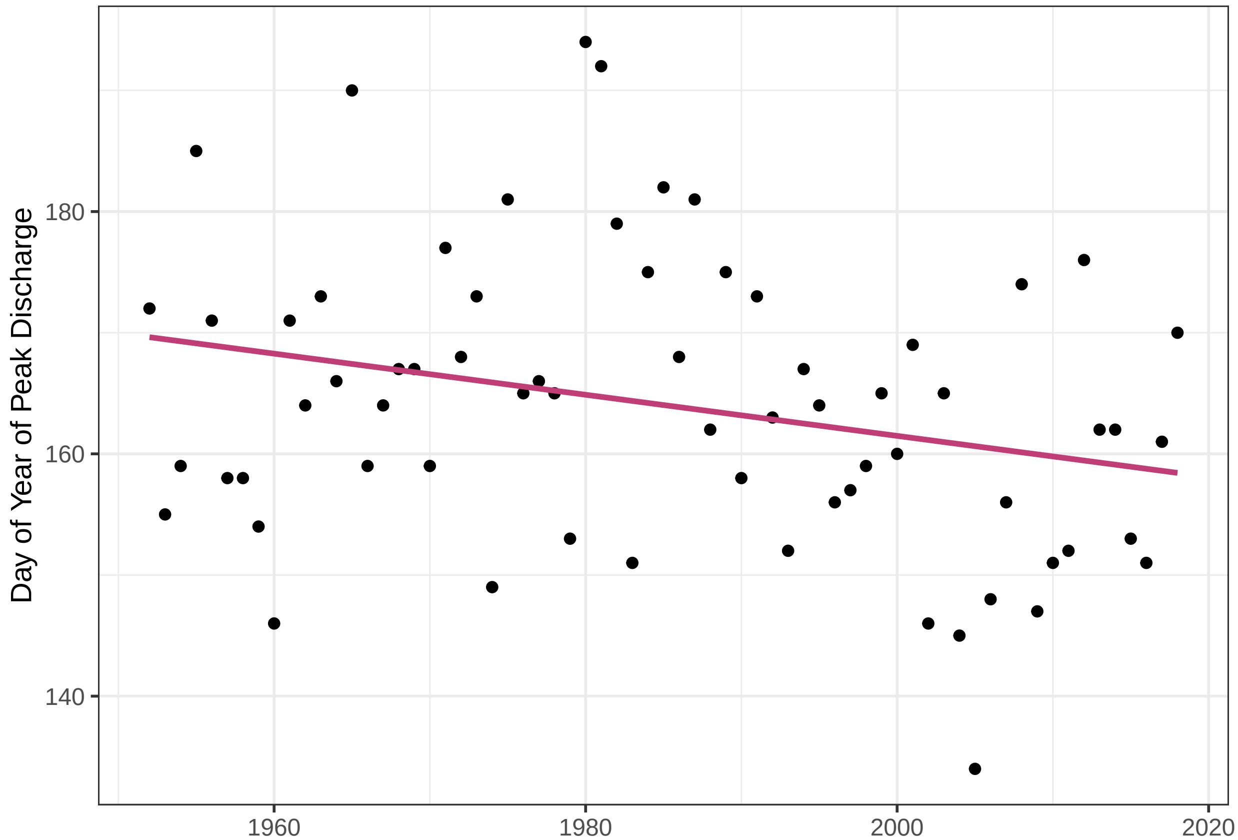


Figure 10: Monthly average maximum temperature for bin 5 near Anchorage along with the trend in temperature shown in blue.

5.2 Snowmelt

After looking at exploratory graphs, it was decided to use day of year of peak discharge as a proxy for snowmelt, instead of day of year of first large discharge increase. This was because peaks would be changing in a similar fashion, and it was more computationally feasible and efficient for analyses. For each latitude bin, the day of year of peak discharge was determined for each year. Then a linear model was made to determine if the day of year of peak discharge was significantly changing over time for each latitude bin. Only latitude bin 5 was found to have a significant change over time in the day of year of peak discharge. As seen in Figure 11, the decreasing trend in the data indicates that the day of year of peak discharge is occurring sooner for the later years.




```
##
## Call:
## lm(formula = DOY ~ YEAR, data = Snowmelt.Discharge.Peaks5)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -26.6361  -8.0117   0.0855   6.0855  29.1217
##
## Coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) 500.85721  145.23473   3.449 0.000994 ***
## YEAR         -0.16969    0.07316  -2.319 0.023532 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 11.58 on 65 degrees of freedom
## Multiple R-squared:  0.07643,    Adjusted R-squared:  0.06222
## F-statistic: 5.379 on 1 and 65 DF,  p-value: 0.02353
```

Figure 11: Year vs. Day of Year of Peak Discharge. Bin 5 is the only Latitude Bin with a significant change in the day of year of peak discharge (p = 0.02353, DF = 65, R2 = 0.062). There is a decreasing trend in the data, indicating the day of peak snowmelt is happening

sooner across 1952-2018.

5.3 Precipitation

We calculated the cumulative annual precipitation and discharge water volume for each year by site in cubic feet per year in order to create a column with the ratio of cumulative precipitation water volume: cumulative discharge water volume. This ratio indicates how the proportion of discharge that originates from precipitation. Figure 12 displays the precipitation:discharge ratio over time for Bin 5. When the precipitation:discharge ratio is less than one, some proportion of discharge is a result from other hydrologic mechanisms such as glacier or permafrost melting.

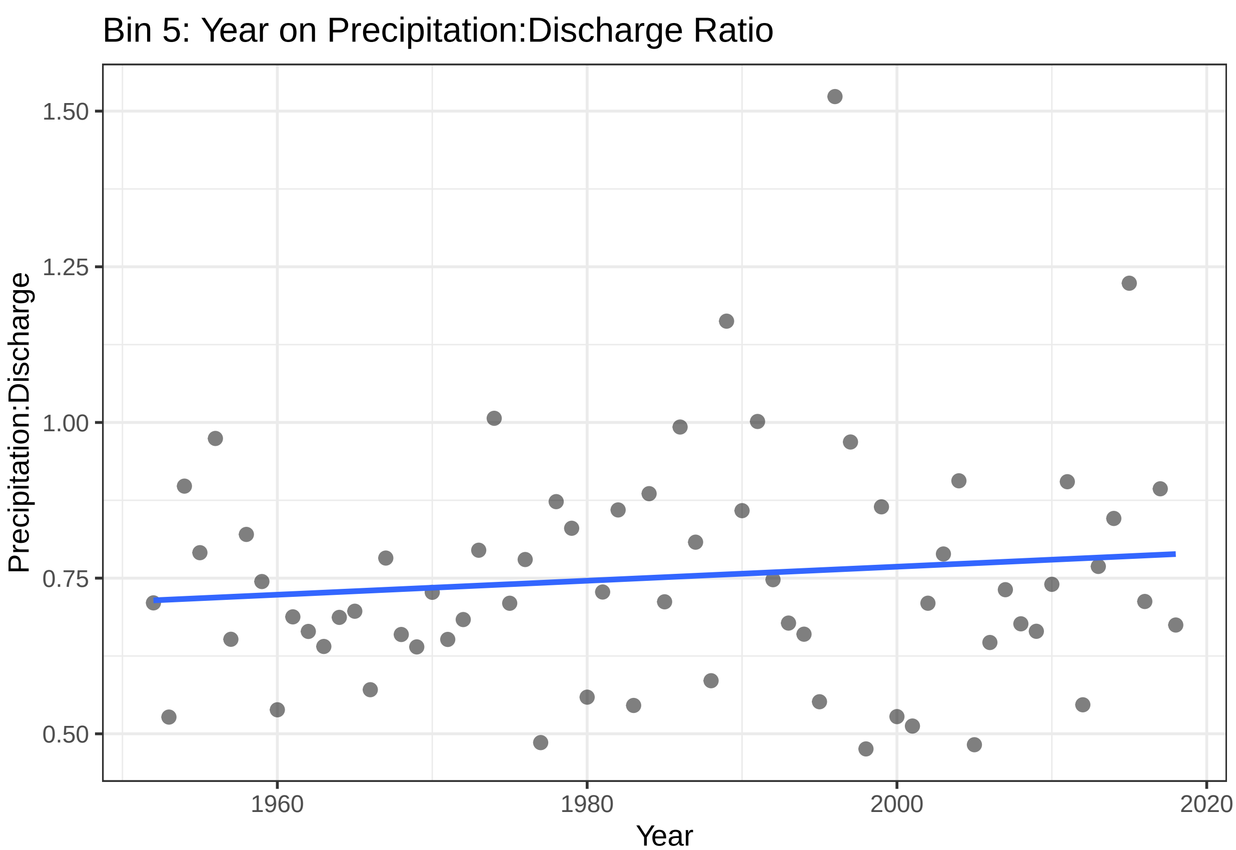


Figure 12: Plot of Precipitation:Discharge ratio across Bin 5's period of record. The precipitation:discharge ratio indicates the proportion of discharge that comes from precipitation. If the precipitation:discharge ratio is less than one, then discharge has inputs other than precipitation, potentially permafrost and glacier melting. As most of the data over the entire period of record falls below the ratio of one, discharge in Bin 5 has other inputs, depending on drainage area. The overall preciptation:discharge ratio is increasing over the period of record, however, potentially because melting of stored water in permafrost and glacier has already occurred due to climate change.

```
##
## Call:
```

```
## lm(formula = Precip_Discharge_Ratio ~ Year, data = PrecipDischargeVolume)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -1.6706 -1.0196 -0.5607 -0.1582 13.7358
##
## Coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) -16.931105   8.066866  -2.099   0.0364 *
## Year          0.009256   0.004063   2.278   0.0231 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 2.074 on 479 degrees of freedom
## Multiple R-squared:  0.01072,    Adjusted R-squared:  0.008656
## F-statistic: 5.191 on 1 and 479 DF,  p-value: 0.02314
```

The final linear equation of this precipitation:discharge linear model is Y=-16.93 + 0.0092(Year). A one-year increase in time increases the precipitation:discharge ratio by 0.01 units. This trend is visible in Figure 12.

5.4 Discharge

To analyze the seasonal trend of discharge of each bin, the monthly average discharge data are applied, which are calculated from the daily discharge data. In order to make sure the result is correct and reasonable, choosing the right period of time to do time series is very important. The criteria for selecting optimal period of records is to make sure it covers at least 30 years most recent data if possible. For Bin 1, it only has 5 years of data, which is not useful to do time series on it. For the gaps in the data, if there is a huge gap(>3 years), drop it to keep the most recent data, if the gap is small(<= 3 years), the average discharge of that month over periods is used to fill the gap.

Seasonal Mann-Kendall tests are performed on the monthly time series to determine if there is a change in discharge over the period of record. If there is a statistically significant trend ($p<0.05$) over the period of record, the seasonal sen's slope test is used to determine the average magnitude of the change. In order to remove the impact of river volume, sens'slopes are normalized by divided by average discharge over period of records. Figure 13 shows that except for bin 1 and 3, discharge of other bins shows small seasonal change and since the sens'slopes are all positive, discharge is slightly increasing over time. However, there's no clear trend shows that seasonal change of discharge has positive or negative relationship with latitude, which cannot supports the hypothesis that climate change is having larger impacts near the poles.

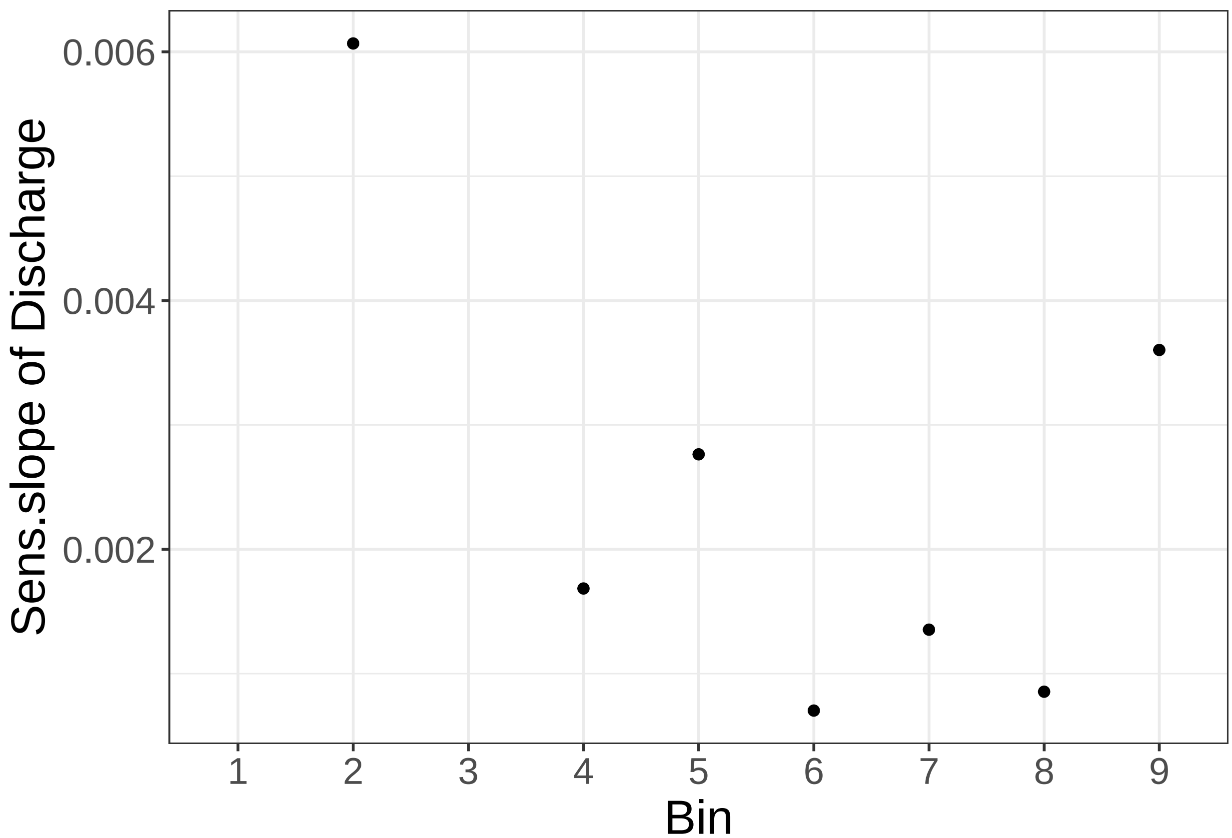


Figure 13: Annual trend in stream discharge divided by mean discharge for each bin.

6 Summary and Conclusions

Latitude Bin	Temperature Change, °F/yr	Annual Percent Change in Discharge	Change in Day of Year, days/yr
1	-0.26	No change	No change
2	0.1	0.61	No change
3	-0.02	No change	No change
4	0.08	0.17	No change
5	**0.04**	**0.28**	**-0.17**
6	0.05	0.07	No change
7	No change	0.14	No change
8	No change	0.09	No change
9	0.16	0.36	No change

One possible reason for such little impact of temperature on the date of peak snowmelt is the months in which temperature trends occur. For example, though the overall temperature for Bin 5 shows an increasing trend, the spring months of March, April, and May actually show a cooling trends. Summer and fall months however show increasing temperature trends that outweigh the cooling trends of earlier months. As the sen's slope is the median of all monthly trends, this nuance is not exhibited in the overall temperature trend. Warmer summer and fall seasons may have little impact on the date of peak discharge.

The analyses in this study do not strongly support the original hypotheses. The overall temperature trends do not show polar amplification, in part due to a small number of latitude bins and only one temperature site per bin. Similarly, there is no statistically significant relationship between change in discharge over time and latitude. There were only five sites that had both statistically significant trends in temperature and discharge, and these five sites did not show a relationship between temperature and discharge or temperature and day of peak discharge.

Future analsyses should take a more nuanced approach to investigating the impacts of climate change on discharge of Alaskan streams. Temperature data show a need to investigate the seasons that will have direct effects on stream discharge rather than looking at the year as a whole.

6.1 Limitations

This study had many limitations, which likely contributed to the inability to prove our hypotheses. In order to perform analyses within an appropriate timeframe, it was necessary to constrain the number of sites used in the study. However, having only ten latitude bins, each with one point representative of all possible conditions within that latitude range, severely reduced the ability to understand how being located near coasts, mountains, cities, etc affected climate and discharge at each site. Furthermore, the lack of accountability for the physical characteristics of each stream and its watershed likely resulted in many of our models explaining little of the variation within the data. Most climate stations were not located near discharge sites, and rather were only located within the same county. Alaskan counties are extremely large in area, so in some cases climate data was obtained hundreds of miles away from the discharge site. This hindered our ability to accurately see the role of temperature and precipitation on discharge. The period of record across each latitude bin was inconsistent, with one bin having as little as seven years of data to another having over fifty years of data. Short periods of record coupled with inconsistencies across latitude bins made it difficult to find statistically significant changes and to make reasonable comparisons across various sites. In order to keep periods of record as consistent as possible, discharge data was used as a proxy for snowmelt. However, using data related to snow cover and/or albedo would have been far more appropriate when attempting to analyze changes in snowmelt, as there are many factors that could affect snowmelt and discharge in different ways.

7 References

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Walsh, J. et al., 2014: Ch. 2: Our Changing Climate. J.M. Melillo, T. (T. C.. Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program, 19–67.

The Climate Science Special Report estimates that maximum temperature increases in Alaska since between the first half of the 20th century and the past 30 years have been 1.43 degrees F (https://science2017.globalchange.gov/chapter/6/).