*CEWA568 Final Project Report*
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# Snowpack and streamflow analysis in the South Fork Tolt River Basin

**March 19th, 2021**

***Github:*** *https://github.com/ginevmoore/CEWA568_final_project*

## 1. Abstract

With a recorded increase in global temperatures in recent decades, along with a projected continuation of that trend in the future, it is essential to understand the physical systems that are likely to change as a result of a warming climate. This study investigates how the snow hydrology in the South Fork Tolt River basin, on the western slope of the Cascade mountains in Washington state, has been changing over the last 23 years. Using local Snotel and USGS stream gage sites, we identify whether first-order, annual metrics of the snowpack have been changing with time, and further assess the associated downstream hydrologic impacts. We specifically quantify changes in 1) peak snow water equivalent (SWE), 2) the timing and magnitude of spring melt, 3) the frequency of mid-winter melt events, and 4) the timing and magnitude of minimum and maximum discharge rates on the South Fork Tolt River. We provide a z-test analysis indicating that all of these variables have changed but not to a significant extent between the time periods of 1996-2006 and 2007-2020. We provide a visual summary of the timing and magnitude of measured major water year events, and a qualitative interpretation of the impacts of the snowpack on winter and spring discharge rates. A comparison between high and low snowpack years is consistent with existing interpretations showing that if more precipitation falls as rain than as snow throughout the winter, spring-summer flows are projected to decline and flooding events will become more frequent, and potentially higher magnitude, throughout the winter.

## 2. Research Question

The South Fork Tolt River Basin has two major sites for observing hydrologic data. The Skookum creek Snotel site, and the USGS stream gage at the Upper South Fork River. Each has collected hydrologic data for several decades. Considering the magnitude of the impacts caused by potential changes to this reservoir, a thorough study of the behavior of the reservoir was required. Climate change impacts can be devastating. It's impacts can change the form of water supply, altering the snowpacks in the winter. Avalanches, drought, water shortage, and flooding are among the list of implications of climate change. In order to prepare for these threats, the research aimed to identify the likelihood of climate change in this region. The overall question of the research being, could climate change be verified with confidence. The objectives below provided specifics into answering that question.

The three primary objectives of this project are to: 1) identify decadal trends in the timing and magnitude of peak snowmelt, 2) determine whether there is an increase in rapid snowmelt in the spring, and 3) determine whether the frequency and magnitude of midwinter melt events has been increasing in recent years in the South Fork Tolt River Basin (SFTRB) in Western Washington state. Additionally, to address implications for flooding and water resource management, we have also identified the timing and magnitude of minimum and maximum discharge rates at the USGS stream gage site, to determine the effects of a changing snowpack on the hydrology of the basin.

## 3. Rationale and societal Importance

The South Fork Tolt River Reservoir (SFTRR), which is located 16 miles upstream of the town of Carnation, stores 57900 acre-feet of water and supplies 30% of the drinking water for more than 1.4 million people in the Seattle Metropolitan area (South Fork Tolt Watershed Management Plan, 2011). As is the case for most reservoirs, this resource is largely modulated by snowmelt, with the highest water levels in the reservoir after the spring melt, and lowering levels throughout the summer and early fall. Throughout the winter, water levels in the reservoir vary, and flow through the dam is managed to optimize water storage while also managing flood risks (South Fork Tolt Watershed Management Plan, 2011).

Projected warming temperatures in the maritime snow climate of the Cascade Mountains will lead to a higher elevation snow line, further leading to more precipitation during the wet winter months falling as rain than as snow. This change is expected to lead to both a loss of snowmelt for warm-season water storage, as well as increased risk of flooding during the winter months (Marks et al., 1998). Climate models also predict that the annual winter precipitation and temperatures are projected to increase in the Snohomish River Basin (region shown in Figure 1a), with a decrease in precipitation during the warmer seasons (Vano et al., 2009). This motivates developing a deeper understanding of the snowpack in this basin and whether or not it has changed over the last two decades towards these projections. Furthermore, this motivation also warrants an understanding of the hydrologic impacts as a result of changes in the snowpack.

## 4. Methods

### *4.1 Study Site*

The region investigated for this project is the South Fork Tolt River Basin in Western Washington State (Figure 1). The catchment ultimately drains into the Tolt River, then the Snoqualmie River, and ultimately drains into the Snohomish River Basin with a mouth along the eastern coast of Puget Sound in Everett (Figure 1a).

This basin was chosen for both its aforementioned societal relevance, and also because of the availability of applicable hydrologic datasets. In particular, the basin has a stream gage site upstream of the South Fork Tolt River reservoir, with an accumulation area (outlined in yellow in Figure 1c) that is at a high altitude and is largely influenced by changes in the snowpack. In conjunction with this stream gage site, there is also a Snotel site which is located at an elevation and at an aspect that is representative of a large percentage of the terrain that drains towards the USGS stream gage. The close proximity of the two sites, and refined accumulation area of the stream gage, allows us to draw direct connections between changes in the snowpack and downstream hydrologic impacts that are important to water resource managers and flood risk analysis.

The catchment outline and distance to stream gage raster were created using Topo-toolbox and the Topographic Analysis Kit, a Matlab processing toolkits for geomorphology research (Schwanghart and Scherler, 2014; Forte and Whipple, 2019).

This site is also interesting because the terrain is similar and very close in proximity to the North Fork Tolt River Basin, and can be used as an analogue to understand a broader catchment area. In particular, since the North Fork Tolt River basin is not modulated by a reservoir, large precipitation events in the form of rain throughout the winter pose a higher risk of flooding to the Tolt River and the communities downstream.

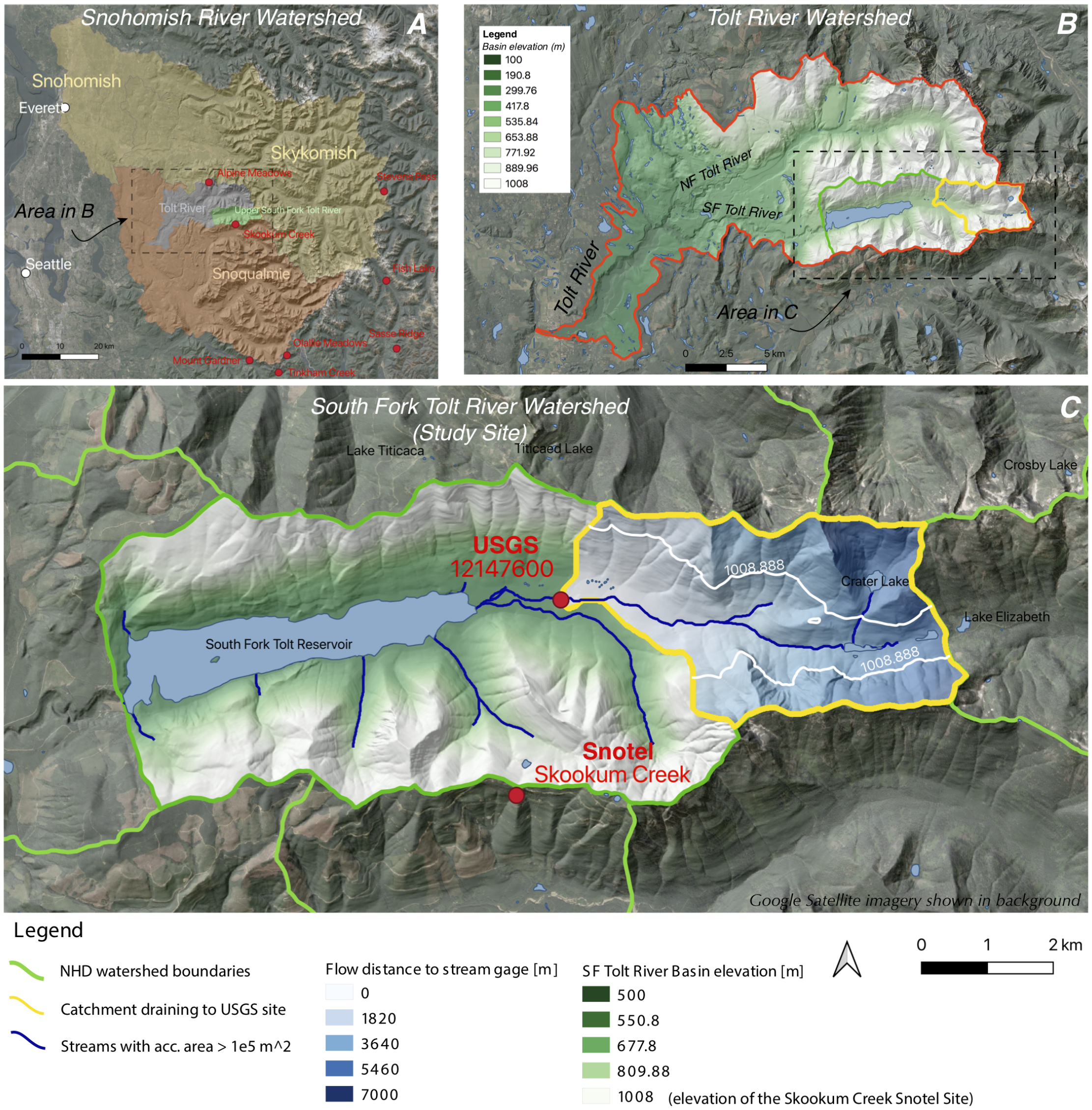


**Figure 1:** The South Fork Tolt River basin being investigated in this study is shown in panel C, with USGS and Snotel sites shown in red. Elevation is colored in white at and above the elevations of the Skookum Creek snotel site (1008m) in B and C to show the general elevations of snow cover that that site is representing. A and B are provided to give geographical context to the basin, which ultimately drains into the Snohomish river near Everett, WA.

### *4.2 Datasets:* (ginevra)

| **Variable** | **Start date** | **End date** | **Units** | **Station** |
|---|---|---|---|---|
| Precipitation | 1995-10-01 | 2018-09-30 | Inches/day | SNOTEL |
| Air temp (mean, min, max) | 1995-08-30 | 2018-09-30 | Degrees F | SNOTEL |

| | | | | |
|---|---|---|---|---|
| SWE | 1995-09-03 | 2018-09-30 | Inches total | SNOTEL |
| Discharge (mean) | 1959-12-01 | 2021-02-04 | cubic feet per second | USGS |
| Water temp (mean, min, max) | 1994-10-28 | 2021-02-04 | Degrees C | USGS |
| Gage height (mean) | 1987-08-15 | 2021-02-04 | Feet | USGS |
| Turbidity (median, min, max) | 2019-12-03 | 2021-02-04 | formazin nephelometric units (FNU) | USGS |

**Table 1:** The different parameters available from the regional SNOTEL and USGS stream gage sites and the dates of availability.

We have downloaded publicly available data from the USGS stream gage site 12147600 which has daily discharge records starting in the 1959 water year. We also downloaded publicly available data from the NRCS Skookum Creek SNOTEL site which has daily snow water equivalent data starting in the 1996 water year (Sun et al., 2019; Yan et al., 2018). The Snotel data was acquired from the Pacific Northwest National Laboratory (PNNL) website which is bias-corrected and quality controlled. Table 1 shows all of the parameters that are available between these two datasets together, along with the time periods that each variable has been collected at a daily cadence.

### *4.3 Analysis*

#### *4.3.1 Data interpretation and collection - Skookum Creek Snotel Site*

An online library of data products provided resources needed to collect Snotel data at the Skookum Creek site. The Pacific Northwest National Laboratory provided complete datasets of SNOTEL sites throughout the region. Those datasets included daily Snow Water Equivalent (SWE) data at the Skookum Creek site for each year of the study. This data was included in conjunction with daily precipitation values, and temperature data. All datasets were accessible via the USDA website.

The Skookum Creek SNOTEL site is representative of local mountain hydrology within the Tolt River basin. The study assumed that snowmelt patterns observed her could be applied to the entire basin. The year range of 1995-2018 is observed in the research as it provides a length timeframe with enough consistency to establish a dependable average within the dataset.

The extensive collection of daily SNOTEL data could be plotted in python using JupyterHUB software. All data points could be visualized to tell the overall story of how snow patterns are changing in this region. One of the main purposes of transitioning to python was to create visual plots of the data for easier recognition of behavioral change within this time period. The central parameter to consider was the SWE data, and all other datasets served to support these observations. The trend of SWE was recorded for each year as shown below.

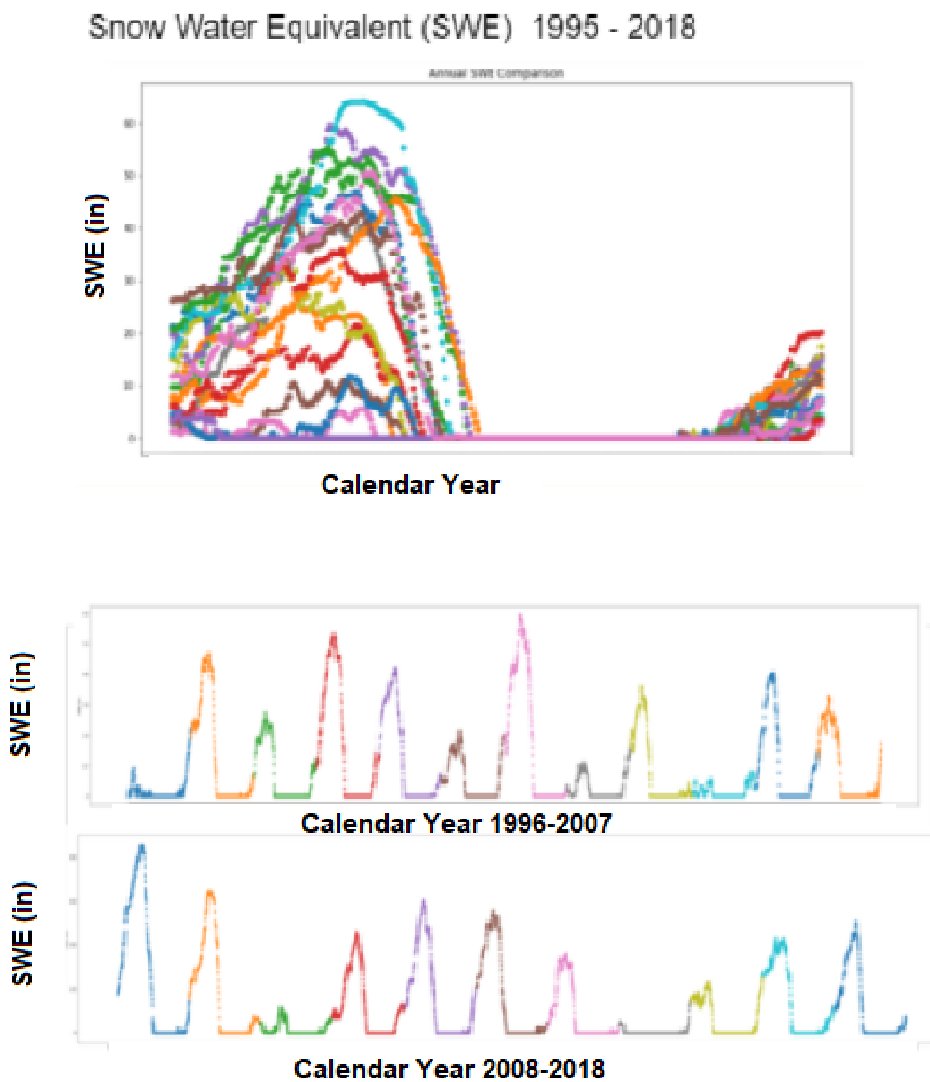


**Figure 2:** All observed SWE (top) and Annual SWE Trend(bottom) Illustrate the variability of snowpack accumulation over a 2 decade window. SWE behavior demands closer examination to answer questions regarding the change of climate, and likelihood of risk for future years.

From observation, a variety of SWE patterns were recorded within the research timeframe. SWE followed a general trend of melting in April most years, with a handful of exceptions. Peak SWE years were followed by SWE shortages and vice versa. In order to draw conclusions from this dataset, a thorough examination through Z-tests were conducted at a later point in the analysis. See section 5.2 below.

Analysis of SWE was closely tied to observations of daily temperature and precipitation. The overall trend regarding precipitation remained consistent throughout the study and can be accessed in the appendix of this report. A close correlation can be drawn between daily temperature averages and SWE in peak years. The figure 3 below represents the maximum and minimum SWE totals observed in 2005 (minimum) and 2008 (maximum). Notice the exponential increase in snowpack levels resulting from variations by magnitudes of 10 degrees fahrenheit.

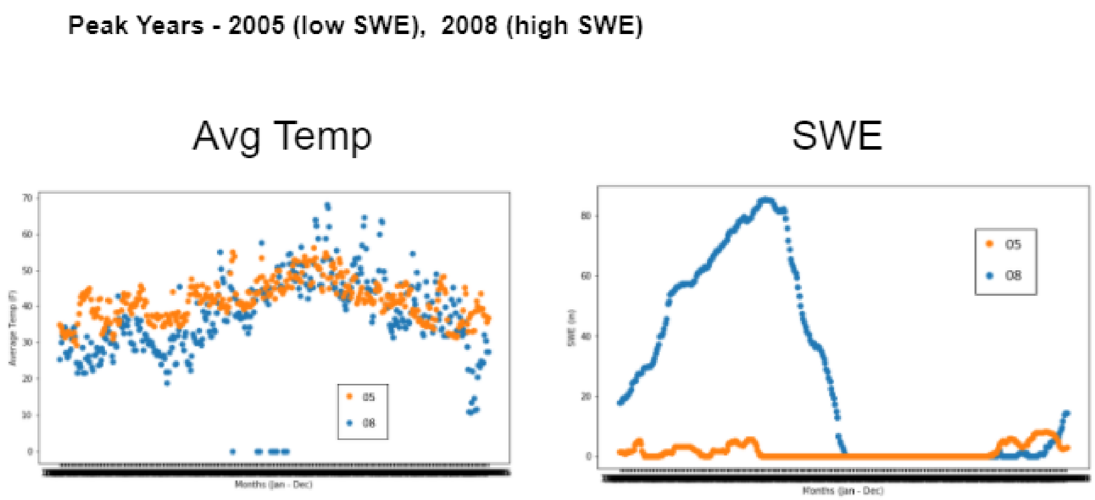


**Figure 3:** Daily Average Temperature plotted against Daily SWE for peak years 2005 & 2008. SWE levels were essentially non-existent in 2005 due to precipitation data arriving in the form of rain during this winter season.

#### *4.3.2 Data interpretation and collection - USGS Stream Gage Site*

To understand the hydrologic impacts of a potentially changing snowpack over the last two decades, we chose two simple parameters to identify for each water year: minimum and maximum annual daily discharge rates. These were chosen as the most pertinent variables to understand given the time available for this analysis. In particular, we set out to identify the timing and magnitude of both of these metrics for each year, to determine if summer low flows have been getting lower in recent years, and if high flow rates are getting higher in winter months as more precipitation is falling as rain. The timing was quantified for both of these metrics to understand if the timing of summer streamflow minimums changes depending on the amount and timing of snowmelt in the spring. Quantifying the timing also helped us to identify if there are trends in the timing of peak flow in recent years, and if that peak flow is primarily dependent on spring snowmelt.

Figure 4 shows the output of a python script developed to plot the time series for any variable in the dataset over a customized time period (plotyear.py). The tools also automatically identify the minimum flow between the months of April-December of a given water year, and the maximum between the months of October to the following September. These month ranges were chosen to limit the automated process to where the maximum and minimum flow values were visually identified, and to prevent the algorithm from detecting maximum/minimum flows from adjacent water years in time. All water years in this study are listed as September of the fall year to December of the spring year to capture the variability in timing of peak and low flows throughout the study period.

An additional tool was developed to plot all of the data from each year in the study period on a single plot to pick out trends in variability and identify the median values for stream flow, or any other variable in the dataset, for each day of the year (e.g. Figure 6). This tool is getminmax.py, and it also identifies the minimum and maximum value for each year, and the timing of those variables, and plots them on a single figure to understand initial trends of the dataset. Finally, the tool also has an embedded high and low water year for this dataset specifically, in order to look at big-picture trends of how the hydrology in the basin is impacted by a changing snowpack (Figure 6).

The annual maximum and minimum discharge values, along with their dates, were added to our master summary table for snow hydrology in the South Fork Tolt River basin. The specific workflow of this wing of the analysis is included in the appendix for reproducibility or application to a similar problem in the future, and is also listed on the github repository at *ginevmoore/CEWA568_final_project/tables/tolt_with_date_differences.csv*.

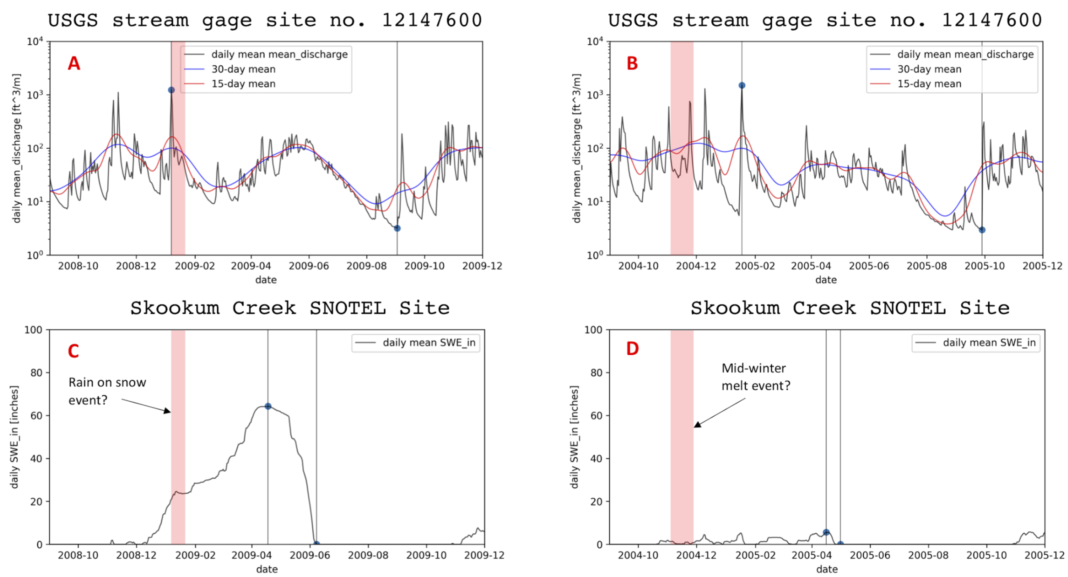


**Figure 4:** Stream discharge (top) and SWE (bottom) time series data for two different water years (left: 2008-2009 and right: 2004-2005) are shown. To look at broader water year trends, the 15-day mean and 30-day mean are shown superimposed on the daily discharge rates. A potential rain on snow event and a potential mid-winter melt event are indicated in the red boxes. The variability in SWE at the Skookum creek site is highly variable, as shown in the difference between the two snow years shown in panels C and D. The minimum and maximum values for each variable are indicated by the points and black lines.

#### *4.3.3 Combining snow and water*

After determining the timing and magnitude of snow and water metrics in the South Fork Tolt River Basin, we used the two datasets together to interpret both quantitatively and visually how the timing and volume of the snowpack in our study area influences water and flooding management in the region. We used date_difference.py to quantify the time period between the start and end of spring melt, and the time period between spring melt and minimum discharge. Additionally, we calculated an average melt rate for each year in melted inches of SWE/day of melt period to understand whether spring melt has become more rapid in recent years. The timing of the major snow and water events is shown in Figure 7 below, and the following section provides details on the statistical analysis to quantitatively understand these results.

### *4.3.4 Statistical Analysis*

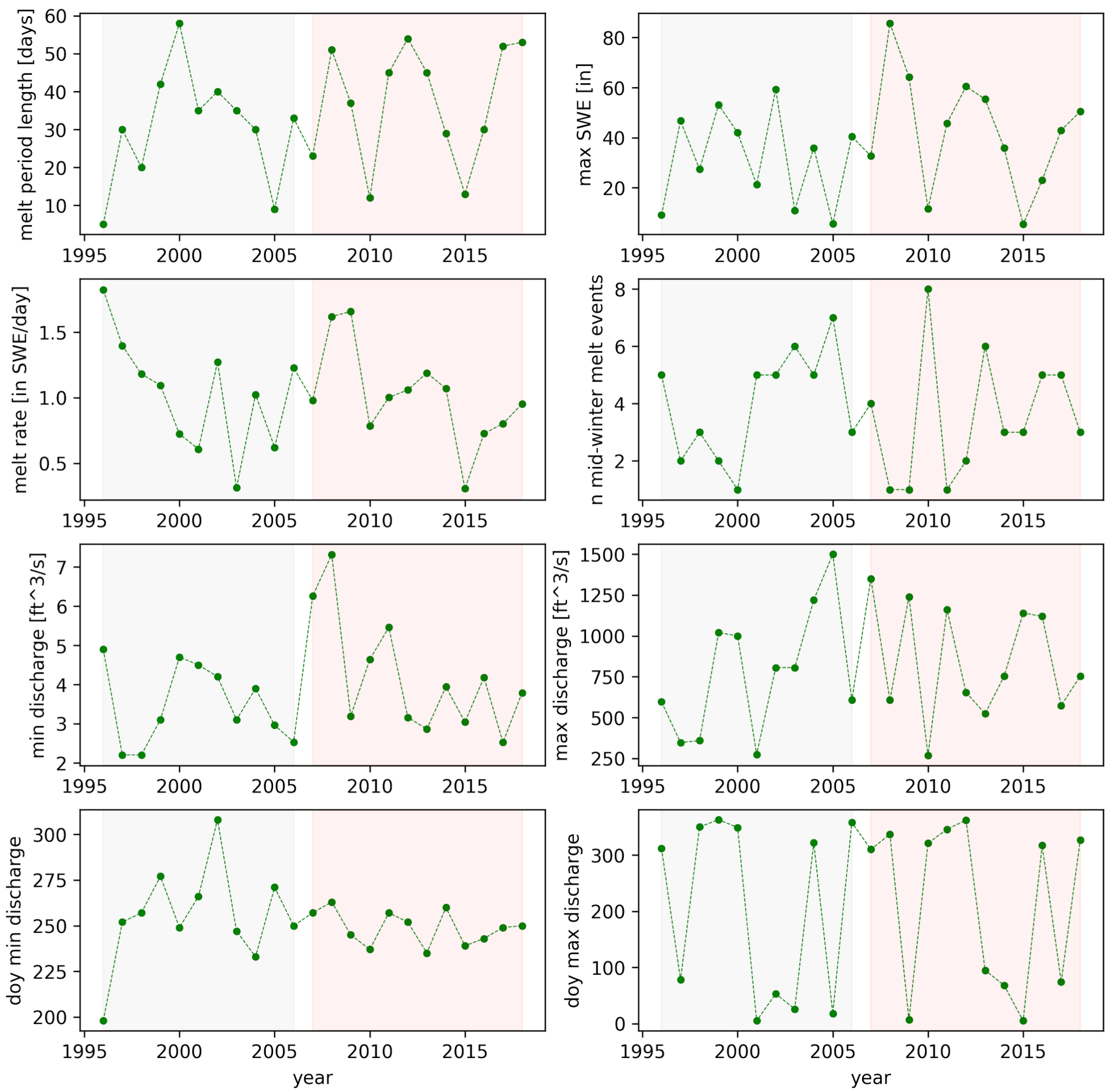


**Figure 5:** The 8 variables in the z test table are shown, with the two time periods being tested against each other shown in grey and red respectively, delimited as the first and second decade in the study period.

Visual observations of the Skookum Creek SWE and USGS Stream Gage data open the possibility of climate change affecting this region significantly. Fortunately, further evaluation is available in a statistical approach. Hypothesis testing of the data evaluates the confidence in significant change taking place over the timespan of observations. The data is split into sections before, and after. The data table shown in the appendix provides the key variables tested in this study. A probability Distribution Function provides a sample space of likelihood of observation given the provided dataset. For example, peak SWE (inches) each year was averaged over the entirety of the timeframe and standard deviation of SWE was calculated.

These values provide a standard Z-test value which accommodates for a 95% confidence that SWE observations in future years will be within a certain range. Grouping the datasets into these two distinct "before and after" groups and performing the Z-test allowed python to test whether changes in SWE were conclusively changing with time. Each of the tested variables are shown in Figure 5 above.

## 5. Results

### *5.1 Visual summary of Snow water Equivalent and daily discharge rates* (ginevra)

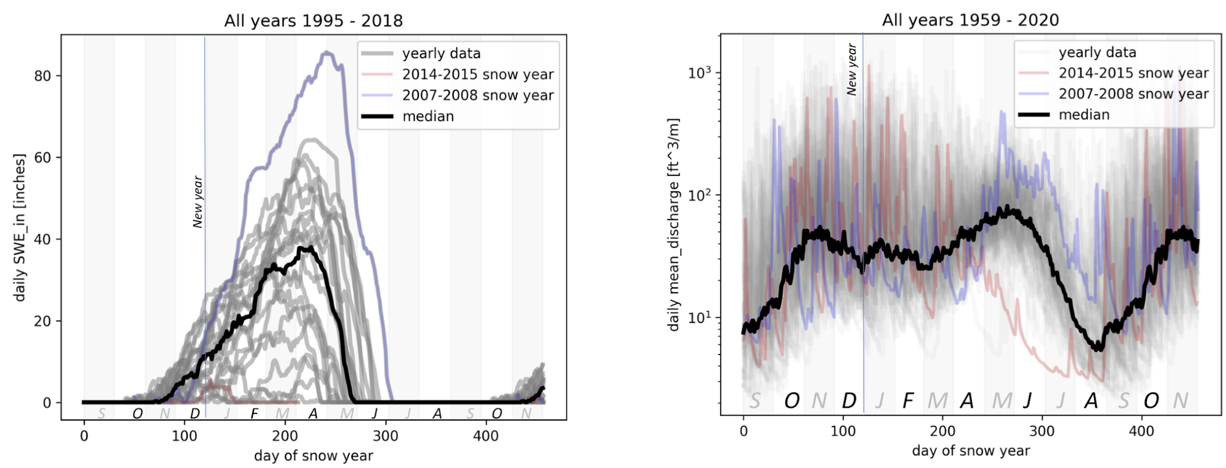


**Figure 6:** All of the years in the respective datasets for SWE (left) and daily discharge rates (right) are shown in grey. The median for each day of the year is shown in black. The blue lines indicate the daily data for the year with the largest SWE values for each dataset, and the red lines indicate one of the years with a very low snowpack.

Five major trends come to light when looking at all of the daily SWE and discharge values side-by-side (Figure 6). These are listed and discussed below. The major takeaway is that if the elevation of snowfall is projected to rise with climate change, ultimately leading to more precipitation falling as rain instead of accumulating in the snow pack, then the associated streamflow is projected to look like that from the 2014-2015 water year, and water managers will need to adjust both how water is stored in the summer months and how flooding is prevented against in the winter months.

***1)*** the snowpack at the Skookum Creek site is highly variable, with some years showing little to no snow accumulation throughout the entire season, and several other years with at least 5 feet of snow at the start of spring melt.

***2)*** When looking at the discharge rates one year at a time, the winter months consistently have the highest streamflow values - which shows in this plot in both the grey lines and the individual red and blue snow year curves. These peak values have a highly variable time period when they occur.

***3)*** When taking the median value of all of the daily discharge rates for a given day of the year, we find that the maximum is in fact not in the winter months, but in the spring following the median period of spring melt. This indicates that the spring flow values are more reliable than the stochastic and high magnitude winter flow events.

***4)*** The snowpack has a dominating effect on spring snow melt. This is identified by the differences between the red and blue curves (for the low 2014-2015 snow year and high 2007-2008 snow year respectively). This visualizes the forcing of snowpack on the streamflow in the spring that we are familiar with, and highlights the dramatic impact on the reliable timing of water flux to the reservoir in the months when it is needed most by changes in how much precipitation falls as snow in this catchment throughout the winter.

***5)*** There are more frequent and higher magnitude spikes in streamflow throughout the winter in the 2014-2015 snow year in comparison to that of the 2007-2008 snow year. This is most likely due to precipitation falling as rain instead of snow throughout the catchment area during the high precipitation months of the wintertime in the Pacific Northwest.

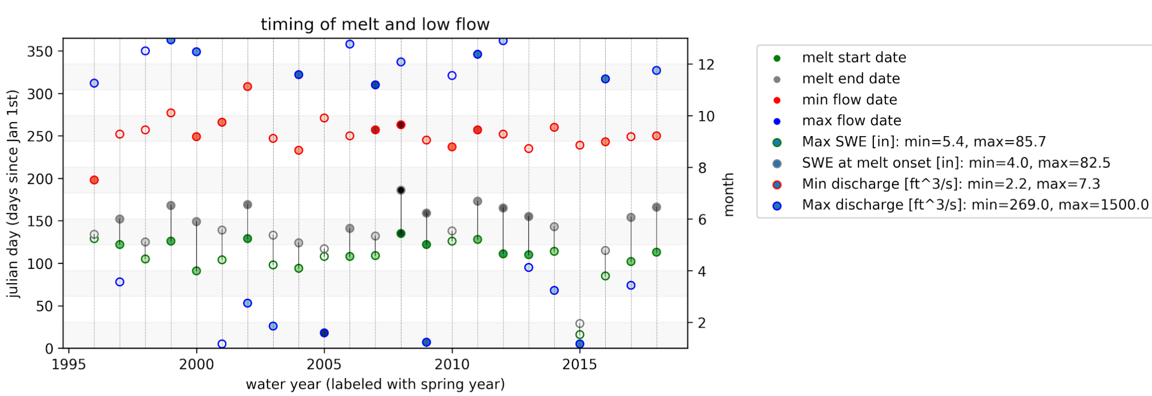


**Figure 7:** Timing of major water year events identified in this study are shown. The gradient colors of the scatter points indicate the annual values of: red=minimum flow value, blue=maximum flow value, green=maximum SWE, grey=SWE at the start of spring melt. These are added to see the variability in these values throughout the years with reference to timing of major snow-year events, with darker colors indicating higher values.

Figure 7 shows visually the variability in timing of the major snow hydrologic events that were sampled over the study period, along with the relative variability of timing between events. The major observations from this plot are listed below.

***1)*** The maximum flow occurs exclusively in the winter months, is highly variable in timing throughout this period, and has a broad range of maximum observed values between 269 - 1500 [ft^3/s]. There does not appear to be any trend in timing over the last two decades.

***2)*** The minimum values consistently occur in August or September, with the exception of a couple of outliers, despite the variability in spring melt timing, indicating that this timing is more likely dependent on when winter precipitation picks up in the following water year than the timing or magnitude of spring melt.

***3)*** The length of the spring melt period does not appear to be shortening over time (indicated by the length of the solid black line for each year) but the length of the melt period appears to be longer when the vertices of the line are darker - which indicates that the snowpack was relatively deeper during those years. There is a potential relationship between the length of the melt season and amount of melt with lower magnitude flows.

### *5.1 Data table*

All essential data were collected in a table within the project excel file for convenience. The key parameters associated with this project include: SWE, melt season, precipitation, discharge, and flow timing; to name a few. The datatable displays all of these variables with their associated units side by side to allow for visual comparison. This comparison allowed the research team to draw comparisons between datasets and verify the consistency of hydrological patterns each year. See the data table figures below in the Appendix.

### *5.2 Statistically significant changes (Z-test)*

The hypothesis tests indicated a possibility that data could be changing between the two periods. A complete table of the z-scores was produced for each major parameter tested in this research. While a majority of the key parameters acknowledged the possibility of significant change, none of the tests allowed the observers to reject the null hypothesis that a change had taken place with certainty. This observation does not remove the possibility of climate change causing permanent pattern changes in the South Fork Tolt River Basin. Further evaluation of these tests may identify trends omitted from this research. The Z-test in regard to the SWE is shown below and the remainder of the tests are provided in the appendix. Failure to reject the null hypothesis doesn't eliminate the possibility of change having occurred over the timeframe. Future observations are likely to support this claim if decadal trends in reduced SWE increase in commonality.

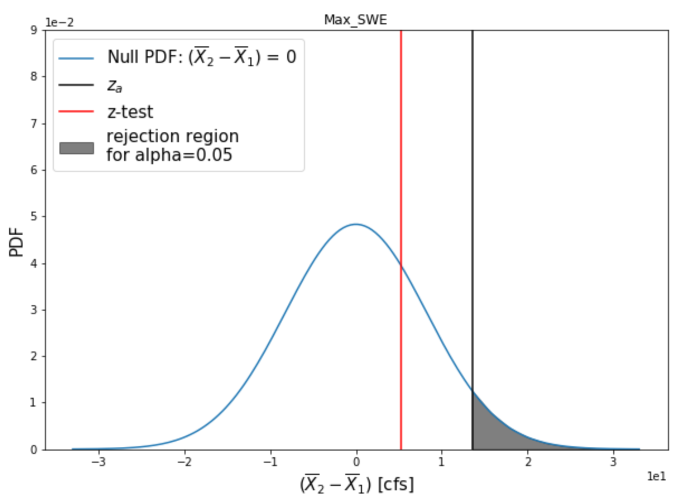


**Figure 8:** The maximum SWE between the two time periods does not reject the null hypothesis that a change has occurred. The 95% confidence level serves as a statistical standard by which these tests are conducted.

| Variable | Max SWE [in] | Min discharge [ft^3/day] | Day of year of min discharge | Max discharge [ft^3/day] | Day of year of max discharge | Melt rate [in SWE/day] | Melt period length [days] | Number of mid-winter melt events |
|---|---|---|---|---|---|---|---|---|
| Z-score | 0.64 | 0.05 | 0.46 | 0.44 | 0.21 | 0.21 | 1.14 | 0.02 |

**Table 2:** Z-score > 1 indicates some change has occurred. Z-score > 1.64 indicates that there has been a statistically significant change above 95% confidence interval.

## 6. Implications and next steps

Water management officials benefit from this research in their ability to forecast streamflow and flooding risk for future water years. The prediction of precipitation patterns as well as the form in which precipitation arrives, allow for planning of water resources. Earlier and reduced runoff from mountain resources may cause drought in the late summer months, along with flooding in the high precipitation winter months as more precipitation falls as rain. Water resource engineering projects designed to understand these trends may account for deficiencies in discharge.

Several meaningful next steps could build on this analysis to provide a deeper understanding of the snow hydrology in the SFTRB. These include 1) incorporating precipitation and temperature values to quantitatively determine the amount of precipitation that is falling as rain or snow throughout the year 2) incorporating MODIS imagery to visualize and quantify typical snow cover distribution in the basin and how well the Skookum Creek site predicts it 3) determining a method for counting the amount of rain on snow and flooding events in a given season using a combination of these added datasets. It would also be interesting to apply the same analysis to the North Fork Tolt River basin (Snotel = Alpine Meadows, USGS gage = 12147470) to identify big-picture trends with a higher signal-to-noise ratio with a larger dataset. Finally, it would be interesting to determine a relationship between these results and climate models, and project how the snowpack and associated hydrology will change given existing climate projections.

## 7. Conclusion

The USGS Stream Gage data in conjunction with the Skookum Creek Snotel site provided thorough understanding of hydrological patterns within the Tolt RIver Basin. Data regarding snowpack, stream flow, and precipitation could be visualized over a 23 year timespan to evaluate climate change patterns in the region. Corresponding tables and plots visualize the data and provide analysis on these results. The data was split in the chronological middle to evaluate statistical likelihood of significant change. While the hypothesis testing didn't identify certain patterns of change considering major climate change parameters, it doesn't rule out the possibility that change has occurred. Continued evaluation of these datasets will provide greater understanding of the effects of climate change patterns on this region.

*** Report length exceeds 10 pages including abstract and tables, but would fit within the limit without these additional pieces. Please excuse the page limit restriction ***

## 8. References

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## 9. Appendix

| Year | Max SWE (in) | Timing of max SWE | SWE value at start of spring melt | Timing of start of spring melt | Timing of end of spring melt | number of dips in SWE (mid winter melt events) | Cumulative Precip (in) |
|---|---|---|---|---|---|---|---|
| 1995 | 4.4 | 8-Dec | 0 | N/A | N/A | 3 | N/A |
| 1996 | 22.2 | 30-Dec | 9.1 | 8-May | 13-May | 5 | 175 |
| 1997 | 46.8 | 14-Apr | 41.9 | 2-May | 1-Jun | 2 | 184.9 |
| 1998 | 27.4 | 11-Mar | 23.6 | 15-Apr | 5-May | 3 | 107.5 |
| 1999 | 53.2 | 10-Apr | 46 | 6-May | 17-Jun | 2 | 147.1 |
| 2000 | 42 | 31-Mar | 42 | 31-Mar | 28-May | 1 | 151.1 |
| 2001 | 21.3 | 14-Apr | 21.3 | 14-Apr | 19-May | 5 | 100.5 |
| 2002 | 59.4 | 30-Mar | 50.9 | 9-May | 18-Jun | 5 | 164.3 |
| 2003 | 15.6 | 31-Dec | 11 | 8-Apr | 13-May | 6 | 111.3 |
| 2004 | 36 | 7-Mar | 30.7 | 3-Apr | 3-May | 5 | 158.7 |
| 2005 | 8.1 | 13-Dec | 5.6 | 18-Apr | 27-Apr | 7 | 127 |
| 2006 | 40.5 | 18-Apr | 40.5 | 18-Apr | 21-May | 3 | 127.7 |
| 2007 | 32.7 | 1-Mar | 22.5 | 19-Apr | 12-May | 4 | 152.3 |
| 2008 | 85.7 | 29-Apr | 82.5 | 14-May | 4-Jul | 1 | 159.3 |
| 2009 | 64.3 | 18-Apr | 61.3 | 2-May | 8-Jun | 1 | 160.4 |
| 2010 | 11.7 | 10-Apr | 9.4 | 6-May | 18-May | 8 | 142.9 |
| 2011 | 45.8 | 4-May | 45.1 | 8-May | 22-Jun | 1 | 182.5 |
| 2012 | 60.5 | 9-Apr | 57.2 | 20-Apr | 13-Jun | 2 | 155.1 |
| 2013 | 55.4 | 29-Mar | 53.5 | 20-Apr | 4-Jun | 6 | 170.6 |
| 2014 | 35.9 | 6-Apr | 31 | 24-Apr | 23-May | 3 | 158.1 |
| 2015 | 14.5 | 31-Dec | 4 | 16-Jan | 29-Jan | 3 | 130.7 |
| 2016 | 24.9 | 30-Dec | 21.8 | 25-Mar | 24-Apr | 5 | 168.9 |
| 2017 | 43 | 10-Mar | 41.7 | 12-Apr | 3-Jun | 5 | 155.5 |
| 2018 | 50.5 | 23-Apr | 50.5 | 23-Apr | 15-Jun | 3 | 172.1 |

| Year | days of melt | timing of low flow | minimum discharge | day of year of minimum discharge | timing of peak flow | maximum discharge | day of year of maximum discharge | timing of peak flow | maximum discharge | day of year of maximum discharge |
|---|---|---|---|---|---|---|---|---|---|---|
| 1995 | | | | | | | | | | |
| 1996 | 5 | 7/16/1996 | 4.9 | 198 | 11/8/1995 | 596 | 312 | 11/8/1995 | 596 | 312 |
| 1997 | 30 | 9/9/1997 | 2.2 | 252 | 3/19/1997 | 347 | 78 | 3/19/1997 | 347 | 78 |
| 1998 | 20 | 9/14/1998 | 2.2 | 257 | 12/16/1997 | 359 | 350 | 12/16/1997 | 359 | 350 |
| 1999 | 42 | 10/4/1999 | 3.1 | 277 | 12/29/1998 | 1020 | 363 | 12/29/1998 | 1020 | 363 |
| 2000 | 58 | 9/5/2000 | 4.7 | 249 | 12/15/1999 | 1000 | 349 | 12/15/1999 | 1000 | 349 |
| 2001 | 35 | 9/23/2001 | 4.5 | 266 | 1/5/2001 | 275 | 5 | 1/5/2001 | 275 | 5 |
| 2002 | 40 | 11/4/2002 | 4.2 | 308 | 2/22/2002 | 806 | 53 | 2/22/2002 | 806 | 53 |
| 2003 | 35 | 9/4/2003 | 3.1 | 247 | 1/26/2003 | 806 | 26 | 1/26/2003 | 806 | 26 |
| 2004 | 30 | 8/20/2004 | 3.9 | 233 | 11/18/2003 | 1220 | 322 | 11/18/2003 | 1220 | 322 |
| 2005 | 9 | 9/28/2005 | 2.96 | 271 | 1/18/2005 | 1500 | 18 | 1/18/2005 | 1500 | 18 |
| 2006 | 33 | 9/7/2006 | 2.53 | 250 | 12/24/2005 | 607 | 358 | 12/24/2005 | 607 | 358 |
| 2007 | 23 | 9/14/2007 | 6.26 | 257 | 11/6/2006 | 1350 | 310 | 11/6/2006 | 1350 | 310 |
| 2008 | 51 | 9/19/2008 | 7.32 | 263 | 12/3/2007 | 607 | 337 | 12/3/2007 | 607 | 337 |
| 2009 | 37 | 9/2/2009 | 3.19 | 245 | 1/7/2009 | 1240 | 7 | 1/7/2009 | 1240 | 7 |
| 2010 | 12 | 8/25/2010 | 4.64 | 237 | 11/17/2009 | 269 | 321 | 11/17/2009 | 269 | 321 |
| 2011 | 45 | 9/14/2011 | 5.46 | 257 | 12/12/2010 | 1160 | 346 | 12/12/2010 | 1160 | 346 |
| 2012 | 54 | 9/8/2012 | 3.16 | 252 | 12/28/2011 | 654 | 362 | 12/28/2011 | 654 | 362 |
| 2013 | 45 | 8/23/2013 | 2.86 | 235 | 4/5/2013 | 524 | 95 | 4/5/2013 | 524 | 95 |
| 2014 | 29 | 9/17/2014 | 3.94 | 260 | 3/9/2014 | 753 | 68 | 3/9/2014 | 753 | 68 |
| 2015 | 13 | 8/27/2015 | 3.04 | 239 | 1/5/2015 | 1140 | 5 | 1/5/2015 | 1140 | 5 |
| 2016 | 30 | 8/30/2016 | 4.18 | 243 | 11/13/2015 | 1120 | 317 | 11/13/2015 | 1120 | 317 |
| 2017 | 52 | 9/6/2017 | 2.52 | 249 | 3/15/2017 | 574 | 74 | 3/15/2017 | 574 | 74 |
| 2018 | 53 | 9/7/2018 | 3.79 | 250 | 11/23/2017 | 754 | 327 | 11/23/2017 | 754 | 327 |

**Table A1:** The final data table used to produce summary figures and Z-test analyses. Green columns indicate the variables that were statistically tested.

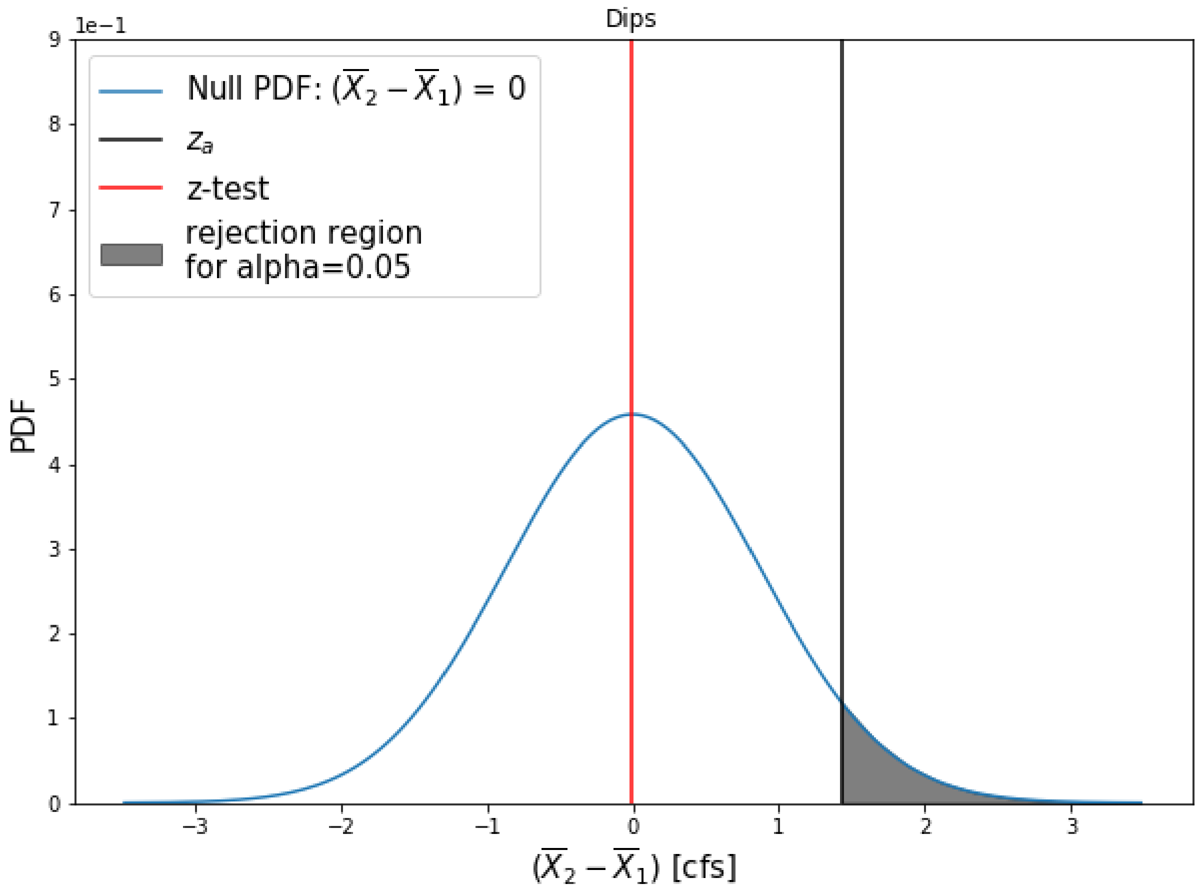


**Figure A1:** Z test for the number of annual mid-winter melt events. The red in the center of the Probability density function indicates that there has been little change in this metric.

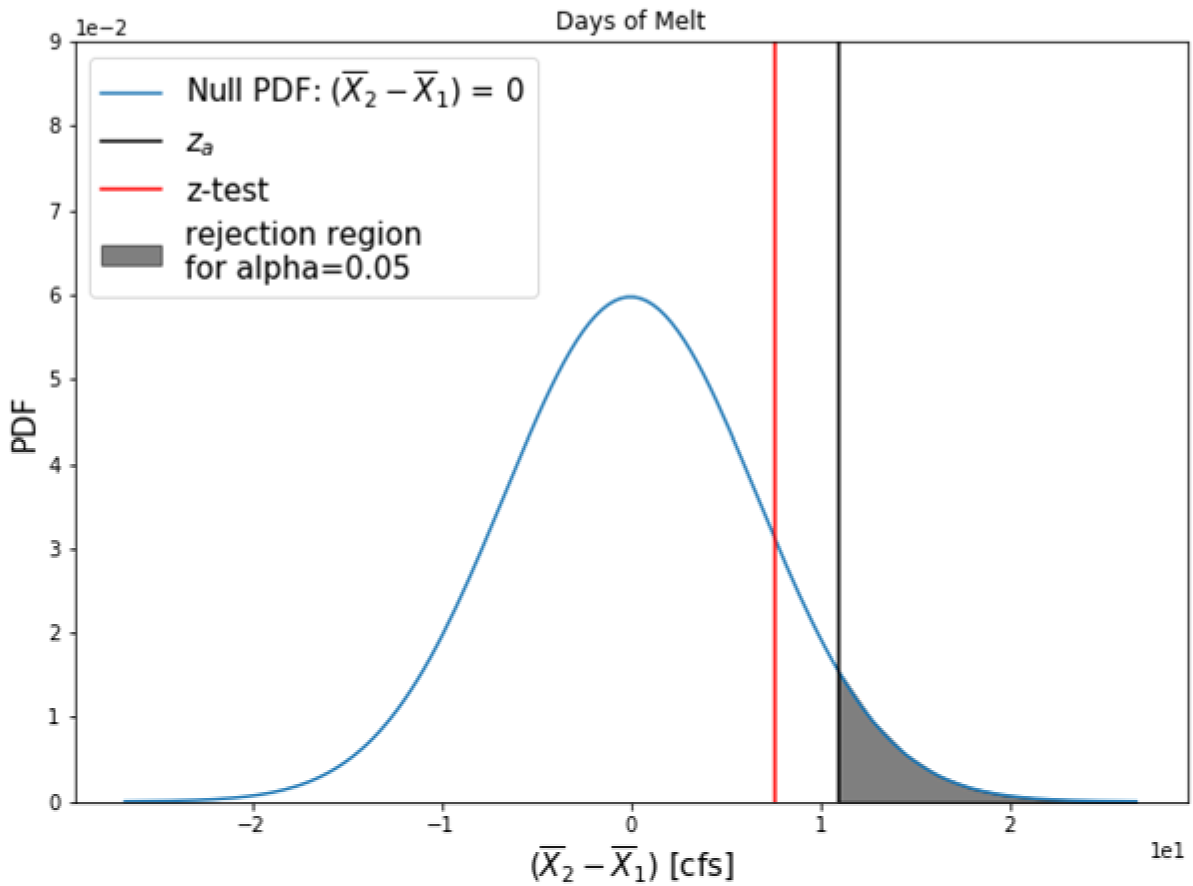


**Figure A2:** Z test for the time period in days of the spring melt period. The red line being to the right indicates that the melt period has been getting longer, not shorter, in the most recent decade, yet not with a 95% confidence interval.

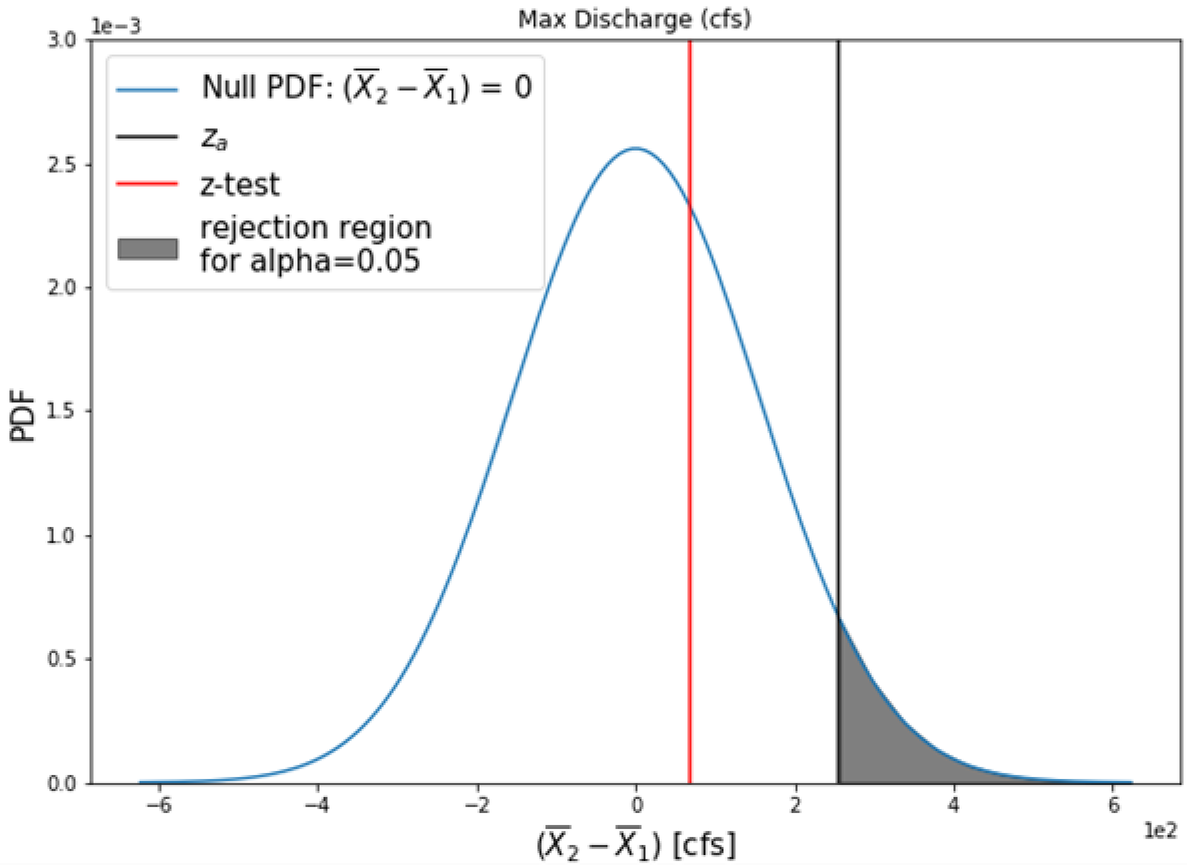


**Figure A3:** Z test for the maximum discharge measured each year. The red line being to the right indicates that the maximum flow rates have increased, but not with a 95% confidence interval.

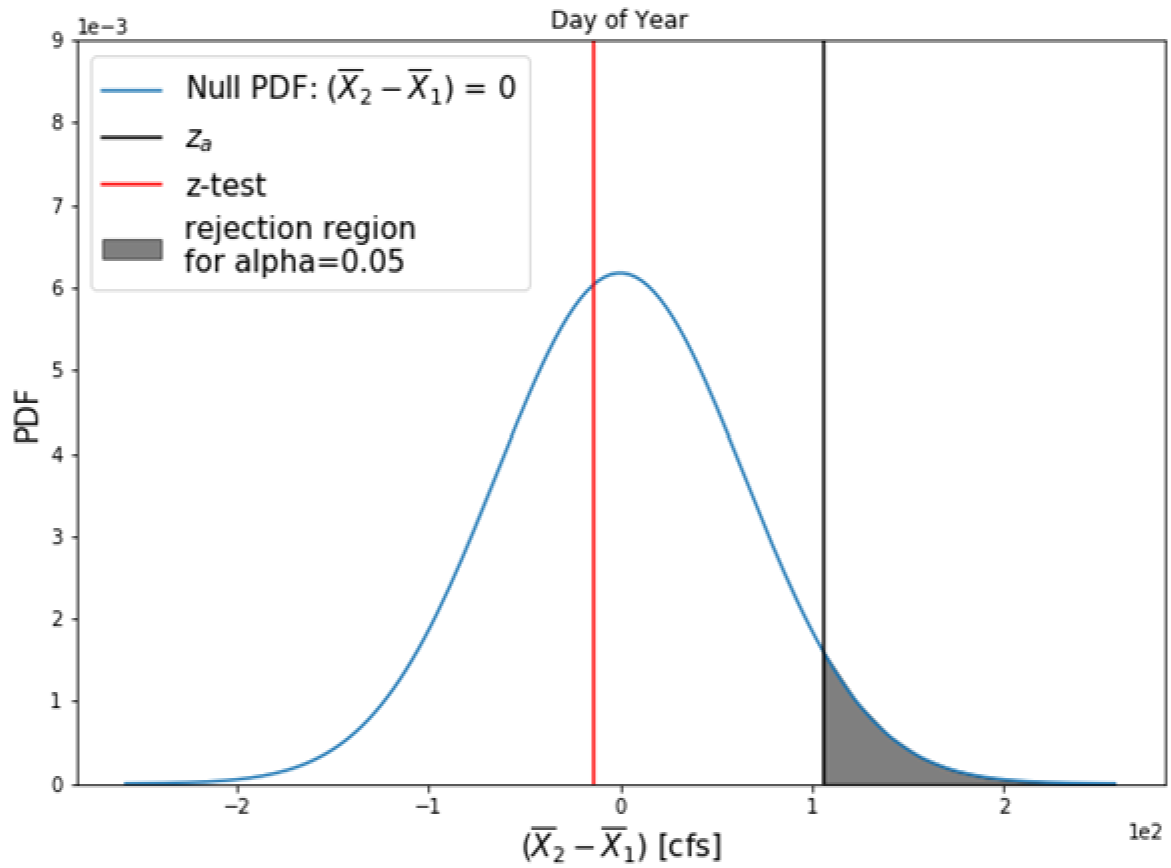


**Figure A4:** The timing of minimum discharge values is shown to have a slight trend towards being earlier in the year.

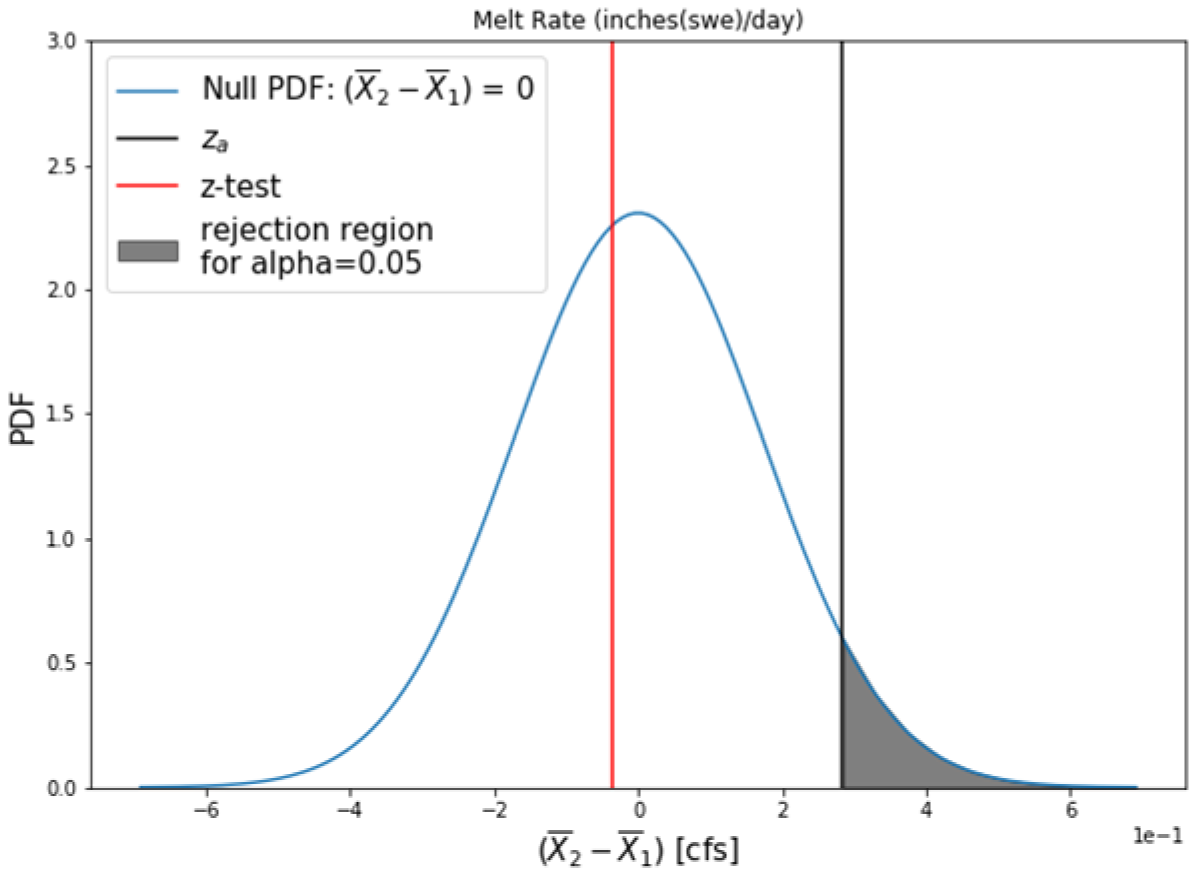


**Figure A5:** The z-test for the melt rate is shown. There appears to be a slightly lower melt rate in the last decade compared to the decade before.

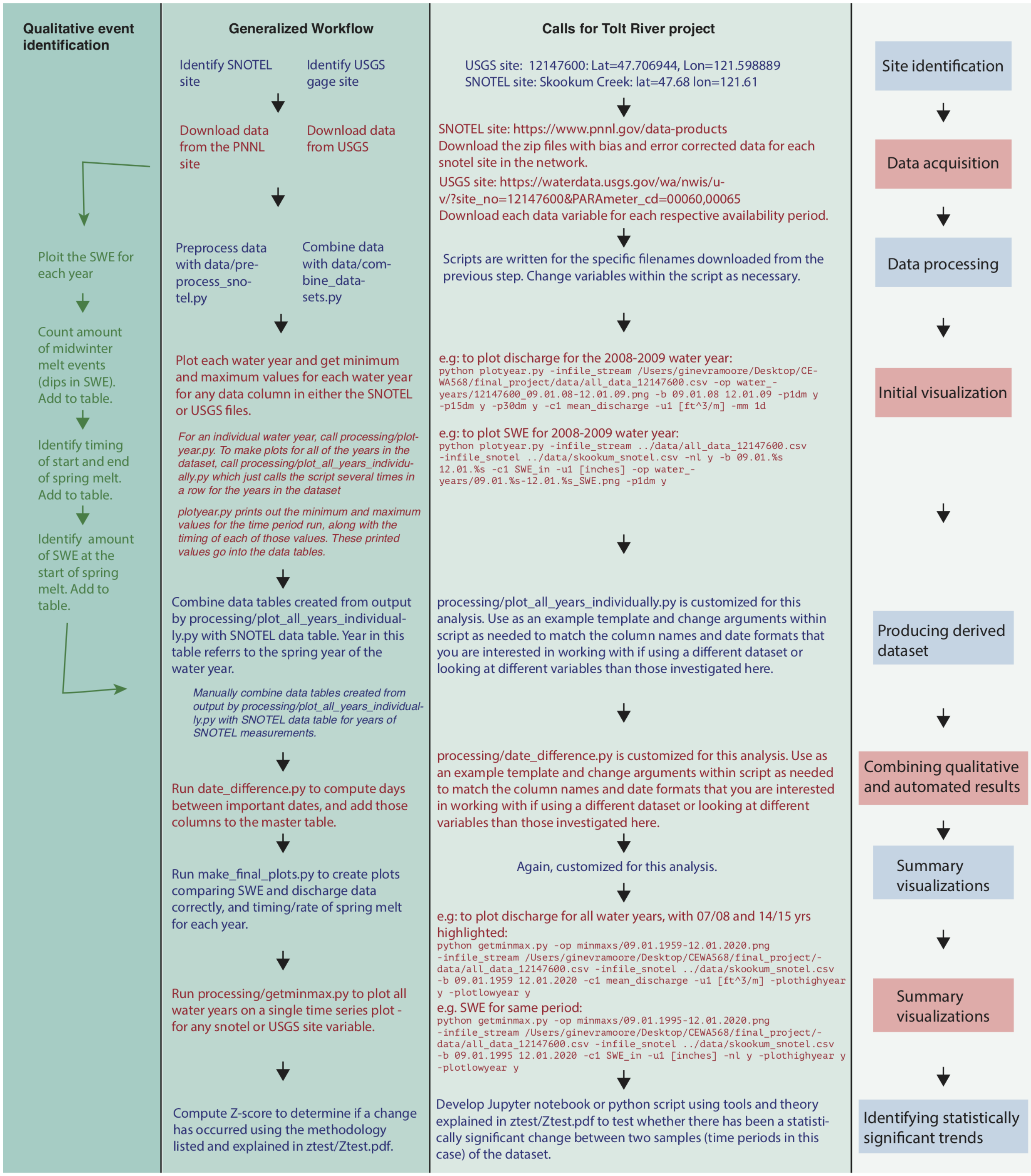


**Figure A6:** The workflow for this analysis is shown from identifying and downloading data, to pre-processing, to visualizing, to analyzing and making finalized plots of the dataset.