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DIRECT AND INDIRECT MODIFICATION OF STREAM FLOW IN THE
FLATHEAD RIVER BASIN IN NORTHWESTERN MONTANA: HYDROLOGIC
PARAMETER DEVELOPMENT AND IMPLEMENTATION

By

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Bachelors of Science in Geology, Edinboro University of Pennsylvania, Edinboro,
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Thesis

presented in partial fulfillment of the requirements
for the degree of

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In Geology

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Geology

Direct and Indirect Modification of Streamflow in the Flathead River Basin in Northwestern Montana: Parameter Development and Implementation

Chairperson: Johnnie Moore

This thesis is comprised of two potential professional papers that were written to be independent of one another. Both papers were written in the context of the hydrology of the northwestern United States. The snowpack stores winter precipitation and releases it in the spring. This snowmelt-dominated streamflow is used by agriculture, municipalities and water-reliant ecosystems. Chapter 1 considered the response of unmodified snowmelt-dominated streamflow to climate change in the Flathead River basin in northwestern Montana from 1940 to 2006. A parameter to quantify annual flow regime components was developed. Drivers of natural variability of flow regime were also considered. A robust statistical analysis resulted in no significant trends in flow regime versus time, and significant trends in flow regime versus annual precipitation. There was no evidence for a linear response by flow regime to climate change. There was no significant linear trend in flow regime over the study period and flow regime was not significantly related to annual temperature in the Flathead River basin. In the upper reaches of the Flathead River precipitation is associated with flow regime variability. Precipitation, in the Pacific Northwest, is associated with natural climate oscillations. Therefore, flow regime variability may be associated with natural climate oscillations such as El Nino Southern Oscillation and Pacific Decadal Oscillation. Chapter 2 compared flow characteristics of dammed and undammed streams for the Flathead River Basin from 1954 to 2006. The quantile-derived flow characteristics were broken into a pre-dam and post-dam study period. Robust regression was used for trend analysis in the post-dam study period. Pearson's correlation analysis was used to compare variance of dammed and undammed streams to downstream streamflow for both the pre-dam and post-dam study periods. Trend analysis showed that the trend in the timing of dammed streamflow was larger and opposite in sign compared to the undammed streams. In general, the dammed streams showed increased variability of the flow characteristics compared to the undammed streams. The dammed stream influenced the downstream flow early in the water year (October to September), but the undammed streams influenced the flow characteristics once snowmelt-dominated streamflow began.

Table of Contents

INTRODUCTION.....	1
CHAPTER 1: FLOW REGIME RESPONSE TO CLIMATE CHANGE IN THE FLATHEAD RIVER BASIN, NORTHWESTERN MONTANA	2
Introduction.....	2
Defining and Development of Snowmelt-dominated Discharge Parameters	6
Datasets	11
Meteorological Data Selection.....	12
Statistical Methods.....	15
Results.....	17
Time Series Analysis	17
Flow Regime versus Meteorological Data.....	19
Discussion	23
Conclusion	29
References.....	31
CHAPTER 2: COMPARING THE EFFECTS OF DAM-MODIFIED AND CLIMATE CHANGE ON STREAMFLOW IN THE FLATHEAD RIVER BASIN, NORTHWESTERN MONTANA.....	34
Introduction.....	34
Datasets	36
Parameter Development.....	36
Statistical Analysis.....	38
Results.....	39
Discussion	47
Conclusion	51
References.....	53

Table of Figures

Figure 1: The Flathead River Basin in northwestern Montana with the North and Middle Fork watersheds delineated. The triangles mark the location of the stream gages used in this study, the SNOTEL station are represented by circles and the Kalispell, MT meteorological station is marked with a star. Wilderness areas (grey), the Flathead National Forest (dots) and the American Waterton-Glacier International Peace Park (hashes) are shown.	6
Figure 2: Discharge record for Middle Fork for water year 2003 (a) compared to ‘classical’ conceptual model of discharge curve (b) and the model proposed by this study (c).	7
Figure 3: Cumulative percentage of the annual discharge record versus day of water year for the Middle Fork of the Flathead River for water year 1940 to 2006.	8

- Figure 4: Developing the flow regime parameters. The estimate start, peak and end of the SDD are demonstrated by the dashed lines for the Middle Fork for water year 2003. a) the discharge curve for the Middle Fork of the Flathead River for water year 2003. b) The spline-smoothed cumulative percentage function (blue) and the unsmoothed cumulative percentage curve (red). c) The second derivative of the spline-fitted cumulative percentage function (blue) and the second derivative of the unsmoothed cumulative percentage curve (red). 10
- Figure 5: Conceptual model representing the critical regimes of the annual discharge. .. 11
- Figure 6: Conceptual model for the estimation of flow regime parameters using the timing parameters derived from the second derivative of the cumulative percentage function. 11
- Figure 7: Correlation coefficients, and confidence intervals with 0.05 significance level, for the analysis of PRISM or Kalispell annual precipitation versus SNOTEL annual precipitation, PRISM or Kalispell annual precipitation versus SNOTEL annual swe, and PRISM or Kalispell mean annual temperature versus SNOTEL mean annual temperature. 15
- Figure 8: Flow regime components versus mean annual temperature for the Middle Fork (right) and the North Fork (left) for water year 1940 to 2006. The trend lines represent significant ($p < 0.05$) trends. 26
- Figure 9: Time series plots for the start, end, duration, and magnitude for the Middle Fork (left) and North Fork (right). There were no significant trends in the flow regime parameters through time for either watershed. 27
- Figure 10: Flow regime components versus annual precipitation for the Middle Fork (right) and the North Fork (left) for water year 1940 to 2006. Cumulative annual precipitation of 3 km^3 is equivalent to a depth of precipitation of ~ 90 and 95 cm for the Middle and North Fork respectively. Cumulative precipitation of 5 km^3 is equivalent to a depth of precipitation of 150 and 160 cm for the Middle and North Fork. The trend lines represent significant ($p < 0.05$) trends. 28
- Figure 11: Discharge curves for the Middle Fork for a high precipitation year (water year 1954) and a low precipitation year (water year 2001). The flow characteristics are similar to what is predicted by the conceptual model. The timing of the low precipitation year is shifted earlier in the year, the limbs of the curve are gentler and the magnitude is smaller compared to the high precipitation year. 29
- Figure 12: The Flathead River Basin in northwestern Montana with the headwater watersheds delineated and the Hungry Horse Dam is shown. The triangles mark the location of the stream gages used in this study. Wilderness areas (grey), the Flathead National Forest (dots) and the American Waterton-Glacier International Peace Park (hashes) are shown. 35
- Figure 13: Mean daily discharge averaged from 1954 to 2006 for the Middle Fork (red), North Fork (blue) and the South Fork (black) of the Flathead River. 37
- Figure 14: Time series plots for the timing characteristics of flow for the Middle Fork (left) and North Fork (center) and the South Fork (right). The same scales were used to illustrate the range of variance of each stream. 44
- Figure 15: Time series plots for the interquantile duration, median flow and interquantile discharge of flow for the Middle Fork (left) and North Fork (center) and the South

Fork (right). The same scales were used to illustrate the range of variance of each stream.....	45
Figure 16: Time series plots for the timing characteristics of flow for the Middle Fork (left) and North Fork (center) and the South Fork (right). Significant trends ($p < 0.05$) are indicated by trend lines.	50
Figure 17: Time series plots for the interquantile duration, median flow and interquantile discharge for the Middle Fork (left) and North Fork (center) and the South Fork (right). Significant trends ($p < 0.05$) are illustrated with trend lines.	51

Table of Tables

Table 1: Results of the trend analysis for flow regime characteristics for Middle Fork and North Fork versus water year.....	18
Table 2: Results of the trend analysis for flow regime characteristics for Middle Fork and North Fork versus mean annual temperature.	21
Table 3: Results of the trend analysis for flow regime characteristics for Middle Fork and North Fork versus annual precipitation.....	22
Table 4: Results of the trend analysis for flow characteristics of the dammed and undammed streams versus water year for water year from 1954 to 2006.	41
Table 5: Descriptive statistics for the South, North and Middle Fork of the Flathead River from 1954 to 2006. The comparison of these statistics is based on the water year, where day 1 of the year is 01 October.	43
Table 6: Results from correlation analysis comparing the timing of flow characteristics of the Flathead River and the Middle, North and South Fork for the pre-dam (1940 to 1952) and the post-dam (1954-2006) study periods.	46
Table 7: Results from correlation analysis comparing the interquantile duration, median flow, and interquantile discharge of the Flathead River and the Middle, North and South Fork for the pre-dam (1940 to 1952) and the post-dam (1954-2006) study periods.....	46

INTRODUCTION

This thesis is comprised of two potential professional papers that were written to be independent of one another. Two of the issues concerning water management and ecosystem stability are global climate change and the damming of streams. The effect of global climate change on streamflow in the northwestern United States is debated. Previous research has suggested that climate change may be affecting the timing of snowmelt, and the snowmelt associated streamflow, in the western United States (Cayan et al., 2001; Mote, 2003 & 2006; Stewart et al., 2005). This work was contradicted by Moore et al. (2007) who reported that the trends in timing of streamflow were more significantly related to the annual discharge than with time in the Columbia and Missouri River basin. Chapter 1 of this thesis investigates the influence of global climate change on the Flathead River basin in northwestern Montana.

The fact that dams influence streamflow is well known. Dams have been shown to modify timing of streamflow characteristics, to increase low flows and reduce the peak flow (Magillian and Nislow, 2005; Singer, 2006; Graf, 2006; Lajoie et al, 2007). They also reduce daily flow variability (Graf, 2006). Some researchers have suggested that under the current climate change models reservoir capacity will need to be increased to meet the water needs of the population of the northwestern United States (Payne et al., 2004; Barnett et al., 2005). Chapter 2 of this thesis compares the trends in the timing of quantiles of flow and related flow characteristics for dammed and undammed streams. This is to put the dam influenced trends in context with the climate change influenced trends in the Flathead River basin in northwestern Montana.

CHAPTER 1: FLOW REGIME RESPONSE TO CLIMATE CHANGE IN THE FLATHEAD RIVER BASIN, NORTHWESTERN MONTANA

Introduction

The Mountainous regions of the western United States rely on snowmelt-dominated watersheds as a source of water for the population and water dependent ecosystems, such as wetlands and riparian habitat, of the western United States. Idaho and western Montana receive over 60% of the annual precipitation as snow (Serreze et al., 1999). The snowpack provides ‘free’ winter storage until the water is released into the streams as runoff in the spring. Recent studies have suggested that global warming is affecting the snowpack in the western United States. Most of the recorded global warming has occurred in the last 30 years, with a 0.2°C increase per decade since 1975 (Hansen et al., 2006). Possibly more important for the northwestern United States, the mean spring (March through May) temperatures in the mid-latitudes are as much as 1.5°C higher than a century ago (Hansen et al., 2006). Mote (2003 and 2006) reported an increase in temperature is overwhelming any increase in precipitation, resulting in April 1 Snow Water Equivalent (SWE) decreasing over the last 50 years. This may indicate an earlier snowmelt season.

Cayan et al. (2001) reported that the ‘spring pulse’ has been beginning two days earlier every decade since 1948, associated with an increase in the mean temperature throughout the western United States. Cayan et al. (2001) interpreted the day when the cumulative departure from the mean discharge was the most negative as the first day of ‘spring pulse’. However, any mean-based algorithm may produce spurious results because the mean has a finite breakdown point of 1, meaning it only takes one outlier to make a mean arbitrarily large or small (Wilcox, 2001). Stewart et al. (2005) reported the onset of ‘spring pulse’ throughout the western United States is occurring one to four weeks earlier

than in 1948. The trend was related to an increase in global temperature. Stewart et al. (2005) used the Cayan et al., (2001) algorithm of the timing of the most negative cumulative departure of the mean but had to constrain the timing to between 15 February and 15 August. The need for arbitrary constraints on the timing of the parameter indicates that it may not be quantifying what it was intended to, i.e., the 'start of Spring snowmelt runoff'. If the algorithm is choosing a day in January as the onset of 'spring pulse' it may not be working as anticipated. They showed trends in the timing of center of mass, which Moore et al. (2007) illustrated was the day of the mean annual flow. So the variable (center of mass) may be sensitive to outliers. Stewart et al. (2005) define the onset of 'spring pulse' as the date when the snowmelt-derived streamflow begins. This usage implies that there is one day in the year when the snow begins to melt, when runoff from melting snow is much more complex: The snowpack accumulates and melts throughout the melt season moving towards runoff dominated by snowmelt from that dominated by winter baseflow.

Moore et al. (2007) avoided the 'spring pulse' concept by applying a temporally broader and procedural scope to their investigation. They examined the day that the 25th, 50th, and 75th quantiles of flow occurred. Quantiles of flow are robust to outliers, have some conceptual value (e.g., the day that half the flow of the year has passed a stream gage) and can be easily examined for changes through time. Using these measures, Moore et al. (2007) reported that the trends in the Missouri and Columbia River basins were more significantly related to annual discharge than with time and questioned the strong response to global warming in snowmelt runoff timing attributed to warming by previous authors. However, the day of various quantiles of flow do not directly record changes in snowmelt derived streamflow, just changes in the timing of runoff in general.

This previous research indicates that global climate change (precipitation and/or temperature) may be associated with changes in the timing and amount of snowmelt streamflow. The various measures used to monitor this change could be useful to water managers, but do not give a deeper understanding how flow regimes are changing in response to climate forcing. For example, ecologists that are concerned about the effects of changes in streamflow on riparian and riverine ecosystems need additional parameters

to understand ecological responses to changes in streamflow. So, from an ecological perspective there are a few additional shortcomings of the previous studies on climate change effects on streamflow: Cayan et al. (2001) only looks at the start of the snowmelt season; Stewart et al. (2005) looks at the timing of the start and middle of the snowmelt season, but it still does not define all of the parameters that are of interest to ecologist; Measures used by Moore et al. (2007) are hard to interpret ecologically and are not represented in the ecological literature.

Climate change induced alterations to the snowmelt-derived streamflow may affect all aspects of riverine and riparian ecology. Salmonid migration and spawning patterns are dictated by the timing of a narrow range of stream discharge (Smith, 1978; Heggenes and Traaen, 1988), making important the rate of change and duration of high flows, not just the beginning of increased flows. Fausch et al. (2001) reported that the ease of invasion by rainbow trout is related to rate of change, magnitude and duration of snowmelt-derived runoff. The success of benthic algae and associated macroinvertebrates can be impacted by duration and magnitude of snowmelt-derived streamflow (Peterson et al., 2001). The riparian vegetation community can also be changed if the rate of change of the snowmelt-derived streamflow, and therefore inundation duration, is altered (Auble et al., 1994). Riparian vegetation recruitment is also contingent on the timing and rate of change of discharge (Mahoney and Rood, 1998; Woods and Cooper, 2005).

There is a need for a suite of streamflow parameters easily derived from hydrographic data to quantify components important to water management and the ecology of systems associated with snowmelt-dominated watersheds. A better concept of what we might be able to quantify is the first step. Spring pulse has eluded researchers so far, perhaps because it does not exist. What may be a more reasonable concept is the time of the year when the baseflow is overcome by snowmelt-derived runoff, referred to here as the snowmelt-dominated discharge (SDD).

A suite of hydrological measures that are well identified in the ecological literature define 'flow regime'. Poff et al. (1997) identified five ecologically critical components of the flow regime of a stream. They are frequency, timing, magnitude, duration, and rate of

change of the streamflow. One of the most prominent methods for quantifying these five components is the indicators of hydrologic alterations (Richter et al., 1996). Olden and Poff (2003) investigated 13 published papers describing hydrologic parameters. Most of the parameters were indicators of hydrologic alteration indices or derivatives of the indicators of hydrological alterations model. The hydrologic indices investigated included the mean, maximum and minimum annual and monthly flows; timing, magnitude and duration of 'low' and 'high' flows; magnitude of 'high' and 'low' flow; as well as the 'high' and 'low' flow variation. They reported that the existing parameters need to be used in conjunction with 'intuitive metrics' for the system being studied (Olden and Poff, 2003).

This study uses mathematical principles to develop and implement a non-arbitrary physically-intuitive hydrologic parameter to estimate annual flow regime characteristics of unmodified snowmelt-dominated watersheds. First, the SDD is identified and separated from the stream discharge record. The SDD is then broken into four flow regime characteristics: timing; duration; magnitude; rate of change. The hydrologic parameters are then used to investigate the changes in flow characteristics through time in the Flathead River basin in the northwestern Montana, United States and whether the changes in the flow regime characteristics of the Flathead River are associated with global climate change. The trends also will be compared to the natural variation of the system.

The Flathead River basin is an excellent test-bed for hydrologic response to climate change (Figure 1). The hydrology is snowpack reliant, and two of the headwater watersheds are relatively unmodified. The North Fork and Middle Fork of the Flathead River will be used in this study. The North Fork Flathead River drains the Flathead National Forest, the Bob Marshal Wilderness and Waterton-Glacier International Peace National Park. The Middle Fork Flathead River drains the Great Bear Wilderness and Waterton-Glacier International Peace Park.

There are several SNOTEL stations in or near the basins at different elevations. This data is the ideal data to use for investigating relationships between meteorological conditions

and streamflow characteristics. SNOTEL data represents meteorological conditions from 1300 to 2100 meters in the study area. The record is too short, with only about 20 years of complete data, to be used exclusively in this study. Continuous daily hydrological records beginning in 30 October 1940 for Kalispell, Montana are available. Parameter-elevation Regression on Independent Slope Model (PRISM) temperature and precipitation products are also available for the Flathead River Basin for the study period. A correlation analysis will be performed to determine if Kalispell meteorological data or PRISM estimates better represent the moderate to high elevation meteorological conditions.



Figure 1: The Flathead River Basin in northwestern Montana with the North and Middle Fork watersheds delineated. The triangles mark the location of the stream gages used in this study, the SNOTEL stations are represented by circles and the Kalispell, MT meteorological station is marked with a star. Wilderness areas (grey), the Flathead National Forest (dots) and the American Waterton-Glacier International Peace Park (hashes) are shown.

Defining and Development of Snowmelt-dominated Discharge Parameters

Determining flow regime characteristics directly from the hydrograph can be difficult without an algorithm to reduce subjectivity. This is demonstrated in Figure 2a, choosing even the first day of snowmelt-dominated stream flow could lead to a wide range of

results. Even on a conceptual/model discharge record choosing the start of SDD is difficult (Figure 2b). This study presents an even simpler conceptual model which may make estimating the day of the start, peak and end of SDD less of a guessing game (Figure 2c). The use of annual cumulative percentage of flow smooth the data and removes the quantity of discharge avoiding the complications of analyzing noisy hydrographs directly.

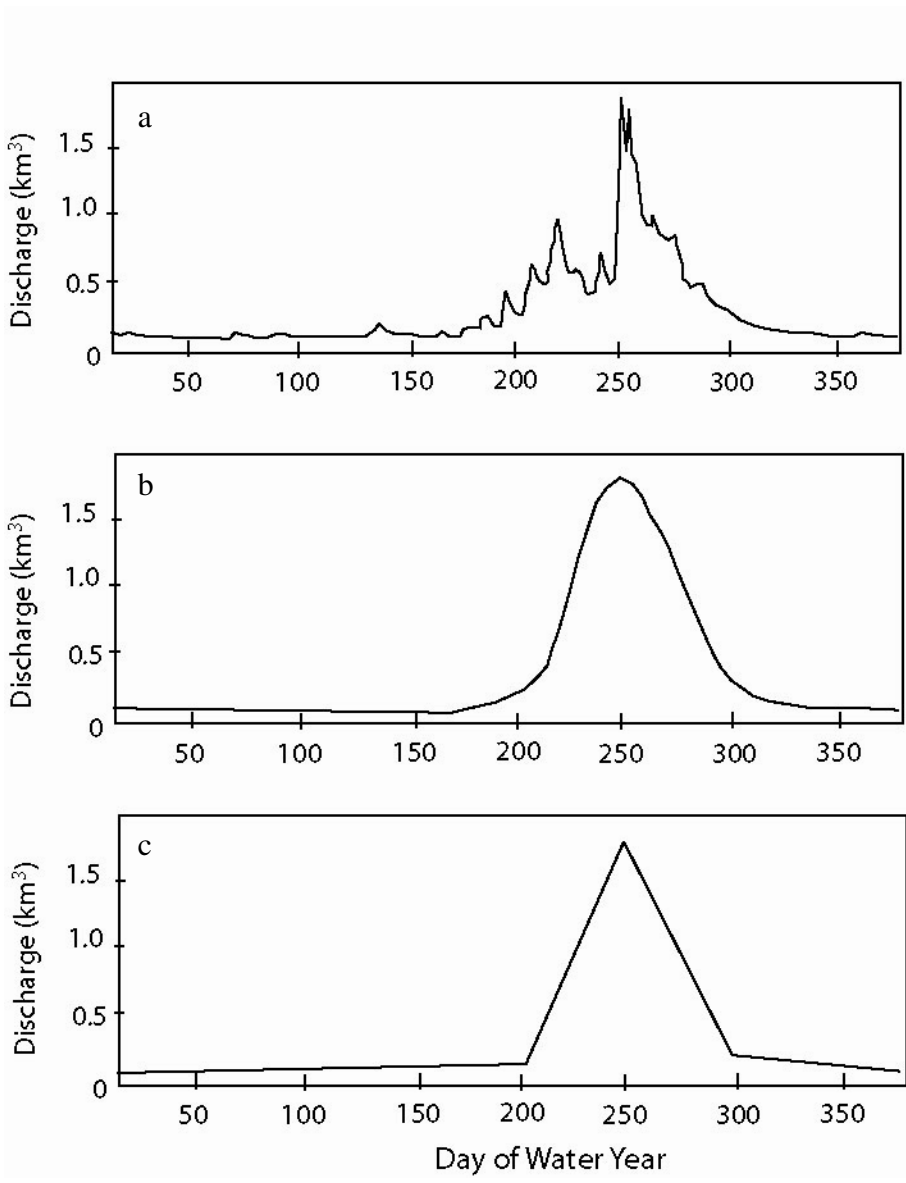


Figure 2: Discharge record for Middle Fork for water year 2003 (a) compared to ‘classical’ conceptual model of discharge curve (b) and the model proposed by this study (c).

The common logistic shape of the cumulative percentage of annual discharge in snowmelt-dominated streams is exploited in this study (Figure 3). The regular shape of the cumulative percentage of discharge allows for the application of a simple algorithm to define flow characteristics.

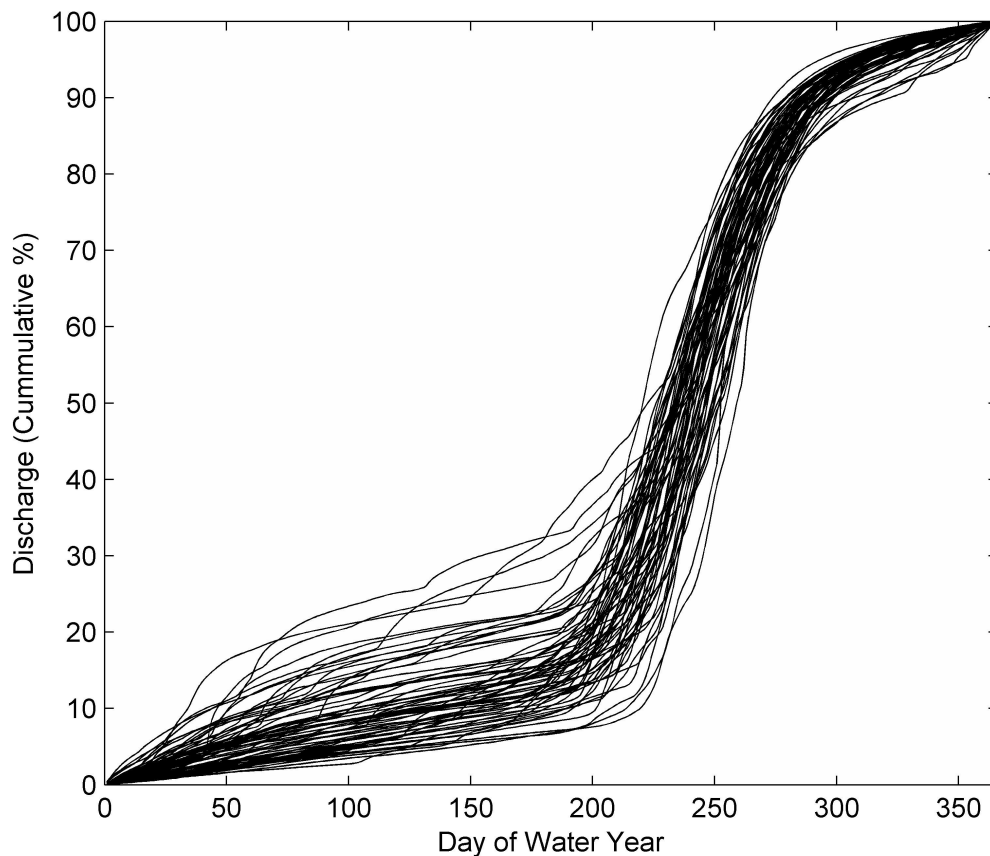


Figure 3: Cumulative percentage of the annual discharge record versus day of water year for the Middle Fork of the Flathead River for water year 1940 to 2006.

While the using the cumulative percentage of discharge smoothes the discharge data, the complexity of the system is still incorporated within it. In order to reduce the complexity, but still retain the general shape, the annual cumulative percentage of discharge is fitted with a cubic smoothing spline. This is illustrated in Figure 4, the red curves represent the unsmoothed data from the discharge record and the calculations using the smoothed data are in blue. The cumulative percentage curves are nearly indistinguishable, but the second

derivatives are significantly different. It is the spline-fitted cumulative percentage of annual discharge, referred to as the cumulative percentage of discharge from this point, which is used to estimate the flow regime characteristics analyzed in this study.

The cumulative percentage of discharge is the integral of the annual discharge record normalized to the annual discharge; therefore it represents the area under the discharge curve (Figure 4a). The area under the discharge curve increases the fastest once the SDD has begun, creating a convex curve in the cumulative percentage of annual discharge (Figure 4b). The addition of area under the curve decreases once the SDD has ended giving the end of the cumulative percentage of discharge a concave shape. The timing of the start and end of the accelerated area increase is estimated by the maximum and minimum of the second derivative of the cumulative percentage of discharge (Figure 4c). The inflection point of the cumulative percentage of discharge represents the day in which the curve changes directions, in this case goes from convex to concave. The inflection point is defined as the point that the second derivative of the cumulative percentage of discharge equals zero. The second derivative-derived parameters can therefore be interpreted to have some physical meaning in an unmodified snowmelt-dominated watershed. The maximum and minimum of the second derivative is taken to be the day of the start and end of the SDD respectively. The inflection point estimates the peak of the annual discharge record or where the SDD transitions from streamflow that gains discharge daily to stream discharge is reduces each day.

Using the estimates of timing of the start, peak and end of SDD the other flow regime characteristics can be estimated. The timing of the beginning and end of the SDD of the annual water year (01 October 30 September) needs to be identified first. This separates the three critical flow regimes of a snowmelt-dominated watershed, the pre-SDD streamflow, the SDD, and the post-SDD streamflow (Figure 5).

Then the flow regime characteristics can be derived. The timing of the beginning, peak, and end of SDD can be defined. The model for deriving additional flow regime characteristics is presented in Figure 6. The duration of the SDD is the difference between the timing of the start of SDD and the end of SDD. The magnitude is estimated

as the total stream discharge (km^3) between the start and end of SDD. The rate of change will be estimated as the mean volume of discharge per day that is added to the stream between the start and peak SDD (ascending rate of change) or the reduction of volume of discharge per day between the peak and end of SDD (descending rate of change).

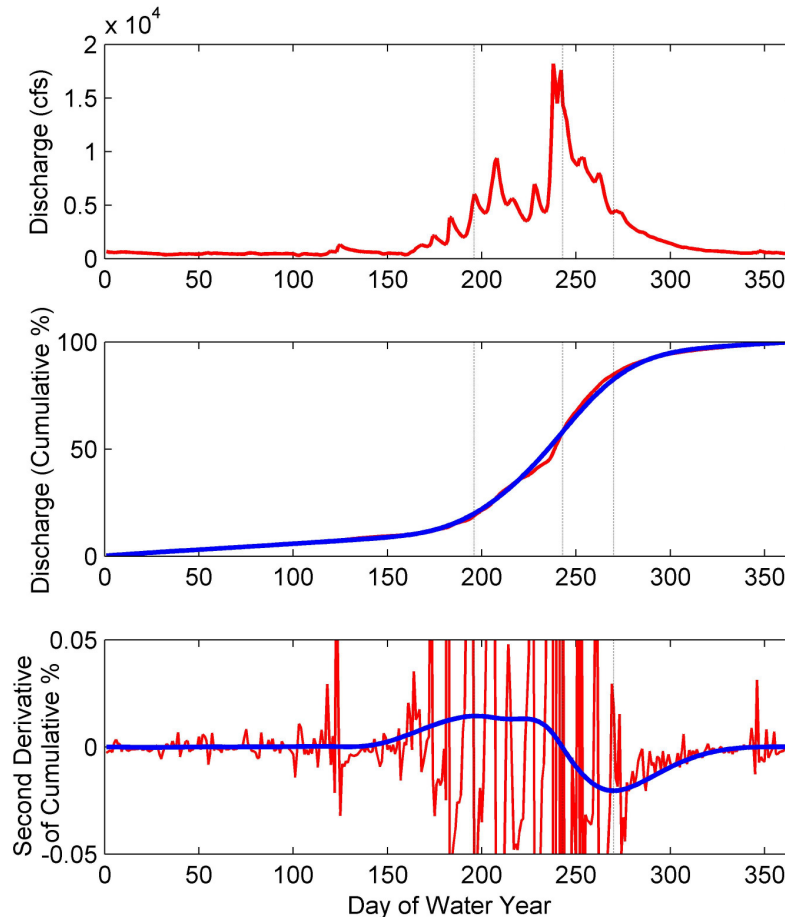


Figure 4: Developing the flow regime parameters. The estimate start, peak and end of the SDD are demonstrated by the dashed lines for the Middle Fork for water year 2003. a) the discharge curve for the Middle Fork of the Flathead River for water year 2003. b) The spline-smoothed cumulative percentage function (blue) and the unsmoothed cumulative percentage curve (red). c) The second derivative of the spline-fitted cumulative percentage function (blue) and the second derivative of the unsmoothed (discrete observations) cumulative percentage curve (red).

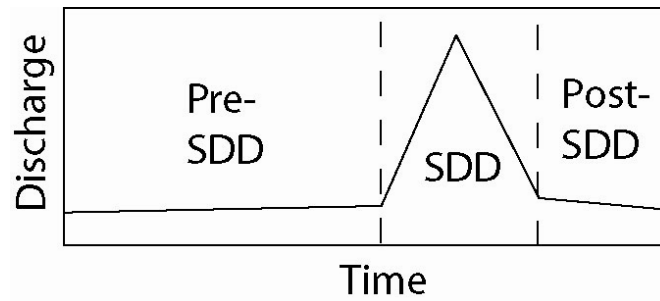


Figure 5: Conceptual model representing the critical regimes of the annual discharge.

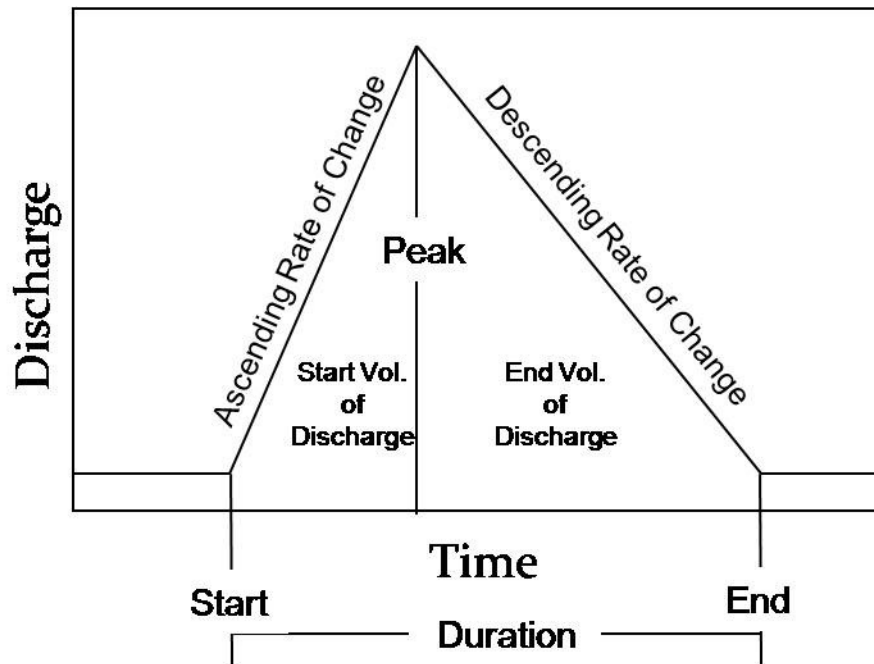


Figure 6: Conceptual model for the estimation of flow regime parameters using the timing parameters derived from the second derivative of the cumulative percentage function.

Datasets

The hydrological data for this study was retrieved from the US Geological Survey (<http://waterdata.usgs.gov>). Daily hydrological data for the Middle Fork Flathead River near West Glacier, Montana (12358500) and the North Fork Flathead River near Columbia Falls, Montana (12355500) from October 1, 1939 to September 30, 2006 were used for this analysis.

There are three sources of meteorological data available for the headwaters of the Flathead River basin. The SNOTEL network is managed by the United States Department of Agriculture's Natural Resource Conservation Service (<http://www.wcc.nrcs.usda.gov/snow/>). The stations take daily measurements of snow water equivalent, precipitation and mean temperatures for moderate and high elevations. Pike Creek Snotel station at 2100 m (site ID: 13a26s), Emery Creek at 1300 m (site ID: 13a24s) and Badger Pass snotel station at 2100 m (site ID: 13a15s) were used for the correlation analysis. The valley-based meteorological station in Kalispell, Montana record (from 1899 to present) is archived by the USHCN (<http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html>). This provides daily measurements of inches of snow, precipitation and mean temperature.

Parameter-elevation Regression on Independent Slope Model (PRISM) is maintained by the Natural Resource Conservation Service (NRCS) of the United States Department of Agriculture and the Spatial Climate Analysis Service at Oregon State. PRISM products are grids that represent monthly temperature or precipitation for the contiguous United States from 1895 to present. Each cell represents an estimated monthly value of mean monthly temperature or accumulated monthly precipitation for a 16 km² area. Monthly PRISM mean temperature and accumulated precipitation products (retrieved from <http://www.wcc.nrcs.usda.gov/climate/prism.html>) for October 1939 to September 2006 were used to estimate annual water year (October to September) meteorological parameters for the North Fork and the Middle Fork basin.

Meteorological Data Selection

Of the three meteorological data sources SNOTEL provides the most relevant daily measurements of snow water equivalent, temperature and precipitation representing the moderate to upper elevations (1300 m to 2100 m) of the watershed. The three SNOTEL stations used in this study are in or near the Middle Fork watershed. The Badger Pass and Pike Creek SNOTEL stations are in the Middle Fork watershed. Emery Creek SNOTEL station is just outside the basin but used in this study to represent the lower end of the watershed. There are no SNOTEL stations in the North Fork watershed. The SNOTEL

stations, however, have a relatively short record for use in a climate change study with less than 20 years of temperature data and less than 30 years of snow water equivalent and precipitation data. The Kalispell, Montana meteorological station has continuous daily measurements of temperature and precipitation beginning in 1895. The drawback to using this data is that the snow measurements are in inches of snow, which makes it difficult to estimate the snow water equivalent from the data. Also, the station only represents low elevation (905 meters) processes.

The PRISM products also have a long record (1895 to present) of temperature and precipitation estimates that are gridded and represents the entire basin. The estimates are only available in monthly precipitation accumulation and mean monthly temperature products. The PRISM products are only available for the contiguous United States. Therefore, the northern third of the North Fork, which is in British Columbia Canada, is not represented. The PRISM product is a model output and not actual measurements of temperature or precipitation.

Since the SNOTEL stations provide the most ideal data but lacks a sufficient record, a correlation analysis was done to determine which of the two remaining data sources best represent the meteorological conditions captured by the SNOTEL stations. The correlation coefficient used for the analysis was the median of a thousand bootstrapped Pearson's correlation analyses as suggested by Wilcox (2005). The confidence intervals were calculated using a bootstrapping with replacement method.

The mean of the daily measurements at the Badger Pass, Emery Creek and Pike Creek SNOTEL stations were used to better represent the moderate to high elevation processes. The annual swe and precipitation were calculated by summing the accumulation (m^3) of the averaged daily values of snow water equivalent or precipitation measurements for the water year (01 October to 30 September). The mean annual temperature was the mean of the daily temperature measurements for the water year. The Kalispell, Montana daily temperature and precipitation data was processed in the same manner. The PRISM products were clipped to the Middle Fork and North Fork watersheds. The PRISM monthly precipitation product is an estimate of the monthly accumulated precipitation for

each grid cell. The accumulated annual precipitation was estimated by summing the precipitation gridded values for the basin for each water year (October through September). The temperature product is an estimate of the monthly mean temperature for each grid cell. The mean annual temperature was estimated by finding the mean of the grid cells in the basin for each water year.

The correlation analysis results are shown in Figure 7. The correlation between the SNOTEL temperature and the Kalispell meteorological data and the PRISM output were basically the same for water years 1940 to 2006 with correlation coefficient of 0.79 and 0.89 respectively. The confidence intervals for the correlation coefficient between SNOTEL precipitation and the precipitation of the other two data sources overlapped. Meaning that they basically represent the precipitation at the SNOTEL stations the same. The correlation between the SNOTEL swe and Kalispell precipitation was insignificant. The correlation between the PRISM precipitation and the SNOTEL swe was small, 0.46, but significant. Therefore, the PRISM products may be the better of the two meteorological sources with long records at estimating the snow and temperature processes.

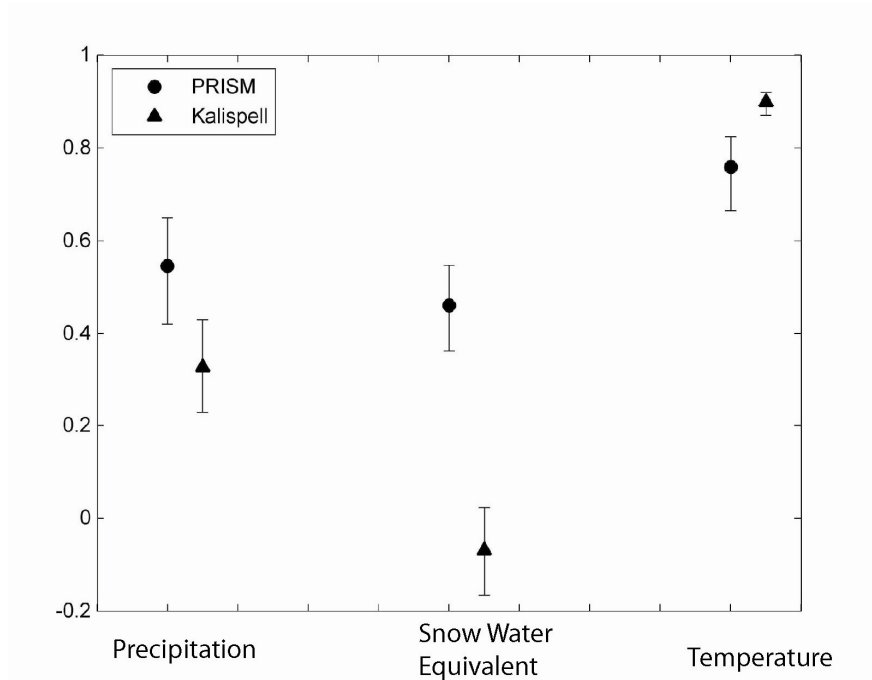


Figure 7: Correlation coefficients, and 95% confidence intervals, for the analysis of PRISM or Kalispell annual precipitation versus SNOTEL annual precipitation, PRISM or Kalispell annual precipitation versus SNOTEL annual swe, and PRISM or Kalispell mean annual temperature versus SNOTEL mean annual temperature.

Statistical Methods

Understanding the changes for flow regime characteristics through time is important from a water management and an ecological perspective. Changes in both water management strategies and ecosystem management may need to be adjusted eventually if the trends cause stream flow characteristics to deviate outside of the natural variation of the system. This study used two separate linear statistical models, one for the analysis of the flow regime changes through time and a second for the analysis of flow regime versus meteorological conditions. Both models were evaluated using the same robust regression method.

The analysis of flow regime versus time uses the multiple linear model

$y = B_0 + B_1x_1 + B_2x_2 + \varepsilon$. Where y is any of the flow regime characteristics, x_1 is the water year and x_2 is the total annual discharge. Moore et al. (2007) found that the trends in the timing of quantiles of streamflow were significantly influenced by the annual discharge.

To account for this a first-order multiple linear model was used to incorporate annual discharge into the equation, thereby reducing the influence of annual discharge on the trend (Ott and Longnecker, 2001). The specific equations used in this study are as follows where WY is the water year and TQ is the total annual discharge:

$$\textit{Start of SDD} = B_o + B_1(WY) + B_2(TQ) \quad (1)$$

$$\textit{Peak of SDD} = B_o + B_1(WY) + B_2(TQ) \quad (2)$$

$$\textit{End of SDD} = B_o + B_1(WY) + B_2(TQ) \quad (3)$$

$$\textit{Duration of SDD} = B_o + B_1(WY) + B_2(TQ) \quad (4)$$

$$\textit{Rate of Change} = B_o + B_1(WY) + B_2(TQ) \quad (5)$$

$$\textit{Magnitude of SDD} = B_o + B_1(WY) + B_2(TQ) \quad (6)$$

The use of a general additive model may improve the results of this analysis by smoothing the total discharge. This could account for non-linear relationships between total discharge and flow regime. The model for the trend analysis of flow regime versus PRISM estimated meteorological conditions was a simple linear model, $y = B_o + B_1x_1 + \varepsilon$. Where y is the flow regime parameter, x_1 is either the annual accumulated precipitation or the mean annual temperature. The specific equations used in this study for this analysis are as follows where Met is either the mean annual temperature or the annual cumulative precipitation:

$$\textit{Start of SDD} = B_o + B_1(Met) \quad (7)$$

$$\textit{Peak of SDD} = B_o + B_1(Met) \quad (8)$$

$$\textit{End of SDD} = B_o + B_1(Met) \quad (9)$$

$$\textit{Duration of SDD} = B_o + B_1(Met) \quad (10)$$

$$\textit{Rate of Change} = B_o + B_1(Met) \quad (11)$$

$$\textit{Magnitude of SDD} = B_o + B_1(Met) \quad (12)$$

A robust regression technique was used to evaluate the models described above. Classical regression methods such as ordinary least squares make assumptions about the distribution and variance of the data that may not be reasonable given the nature of hydrological data. Ordinary least squares assumes that the errors will have a normal distribution, the variance is constant (homoscedacity) and the data is independent. Robust regression methods do not make assumptions of normality or homoscedacity. It still does assume independent data, however. The power of the robust regression technique of weighted least squares is not significantly affected by non-normality or heteroscedacity (Tuki et al, 1986). Autocorrelation, or dependence between data, is not present in the parameters in this study. Therefore, the assumption of independent data is not violated. The standard errors of coefficient (SE) are reported in the tables of results for the regression analysis in this study. Standard error is measure of the variability of the coefficients estimated by the regression method. This is included for completeness.

Results

Time Series Analysis

The results of the trend analysis comparing flow regime to time are summarized in Table 1. There was no linear change in the flow regime characteristics from water year 1940 to 2006 in the headwaters of the Flathead River basin. The median trend p-value was 0.65 and the minimum and maximum p-value was 0.11 and 0.98 respectively. Trends with p-values of greater than 0.05 were considered to be indistinguishable from a trend of zero, or having no change, for this study. Therefore, none of the trends estimated for the flow regime characteristics are discernible from a trend of zero, or having no change through time.

Table 1: Results of the trend analysis for flow regime characteristics for Middle Fork and North Fork versus water year.

	<i>Middle Fork</i>			<i>North Fork</i>		
	<i>Slope</i>	<i>SE</i>	<i>p-value</i>	<i>Slope</i>	<i>SE</i>	<i>p-value</i>
Start of SDD (day/year)	0.014	0.069	0.85	-0.025	0.066	0.72
Peak of SDD (day/year)	0.010	0.049	0.85	-0.0014	0.053	0.98
End of SDD (day/year)	0.028	0.050	0.59	0.015	0.053	0.80
Duration of SDD (# days/year)	0.023	1.5x10 ⁻⁴	0.98	0.025	1.4x10 ⁻⁴	0.97
Ascending Rate of Change (km ³ day ⁻¹ /year)	1.0x10 ⁻⁵	3.0x10 ⁻⁵	0.23	-1.0x10 ⁻⁴	2.7x10 ⁻⁵	.21
Descending Rate of Change (km ³ day ⁻¹ /year)	-1.2x10 ⁻⁵	3.1x10 ⁻⁵	0.11	3.0x10 ⁻⁵	2.6x10 ⁻⁶	0.13
Magnitude of SDD (km ³ /year)	-1.3x10 ⁻³	1.2x10 ⁻³	0.30	-1.1x10 ⁻³	1.2x10 ⁻³	0.36

The Middle Fork and the North Fork showed conflicting trends for two of the three timing parameters but none of the trends were distinctly different from zero change over time. The trend in the Middle Fork timing of SDD indicates that it is occurring later in the water year, whereas the North Fork showed an apparent shift toward an earlier SDD timing. The change in the start of SDD (equation 1) for the Middle Fork was estimated to be one-tenth of a day later every decade since 1940 ($p=0.85$). The trend in the timing of the start of SDD for the North Fork was one-quarter of a day earlier every decade over the study period ($p=0.72$). The range for the day of the year SDD started was 4 April to 25 May, with the median being 1 May for the Middle Fork. This is a difference of 51 days. The range of the timing of the start of SDD for the North Fork was 5 April to 16 May a difference of 41 days. The median day was identical to the Middle Fork, 1 May.

The trend in the occurrence of the peak of SDD (equation 2) for the Middle Fork implied a shift of nearly 0.7 days later in the water year over the study period ($p=0.85$). The peak of SDD in the Middle Fork occurred anytime between 9 May and 16 June, a range of 37 days. In the North Fork had a trend estimating the peak of SDD to be one-tenth of a day

later over the study period (0.98). The peak of SDD in the North Fork was from 9 May to 15 June, similar to the Middle Fork. The trend in the timing of the end of SDD (equation 3) in the Middle Fork suggested a shift of three-tenths of a day later every decade over the study period ($p=0.60$). The earliest the end of the SDD occurred was 2 June and the latest was 19 July. This is a difference of 47 days. The median day of the end was 1 July. The North Fork the trend of the end of SDD was less than two-tenth of a day earlier every decade (0.80). The range of the day of the end of SDD was from 1 June to 15 July, a difference of 44 days.

The duration of SDD (equation 4) was estimated by the trends to be 1.5 and 1.7 days longer in 2006 than in 1940 for the Middle ($p=0.98$) and North Fork ($p=0.97$) respectively. The median duration of SDD for the Middle Fork was 59 days long and ranged from 38 to 99 days long. The North Fork had a median duration of 57 days with a range of 40 to 99 days. The trend in the ascending rate of change (equation 5) for the Middle Fork and the North Fork was 1×10^{-5} ($p=0.23$) and -1×10^{-4} km³/day ($p=0.28$) per year respectively. These trends were a change of less than 0.5% of the record median ascending rate of change for the Middle Fork and North Fork. The descending rate of change (equation 5) showed a similar result. The trend through time was -1.2×10^{-5} ($p=0.11$) and 3×10^{-5} km³/day ($p=0.12$) for the Middle Fork and North Fork respectively. This was less than one-tenth of a percent of the median value of the descending rate of change for the study period for both watersheds.

The trend in the magnitude of SDD versus water year (equation 6) was not distinguishable from zero for either watershed. The Middle Fork had a trend estimated 8.7×10^{-3} km³ less discharge in 2006 than in 1940 ($p=0.30$). This is less than a one percent of the SDD discharge for water year 2006. The trend in the North Fork implied a decrease of 7.4×10^{-3} km³ of the magnitude of flow in water year 2006 than in 1940 (0.36). This is a change amounting to less than 5% of the magnitude of SDD in 2006.

Flow Regime versus Meteorological Data

The results of the trend analysis investigating the relationship between temperature and the flow regime parameters are summarized in Table 2. PRISM products are a monthly

estimate of temperature and precipitation and the discharge data is a daily measurement. In order to reduce issues with using data at two different time scales the annually averaged meteorological conditions were used in this study. The assumption being made is that winter precipitation and spring temperatures will be reflected in the average annual precipitation or temperature. The relationships between mean annual temperature and flow regime characteristics all had p-values greater than 0.05. The trends comparing flow regime characteristics and mean annual temperature were not distinctly different from zero change.

The relationship between the timing of the start of SDD and temperature (equation 7) estimated that for every one degree Celsius increase in mean annual temperature the start of the SDD occurred 2 days earlier ($p=0.20$). The range of mean annual temperature for the Middle Fork was between $-6.6\text{ }^{\circ}\text{C}$ and $-2.4\text{ }^{\circ}\text{C}$. This suggests that temperature accounted for only 8 days of variability in the timing of the start of the SDD in the Middle Fork. The range of mean annual temperature for the North Fork was $-6.5\text{ }^{\circ}\text{C}$ to $-2.8\text{ }^{\circ}\text{C}$. The trend of the start of SDD occurring 1.6 days earlier for every one degree Celsius ($p=0.27$) increase in the mean annual temperature accounted for 6 days of variability in the timing of the start of SDD in the North Fork. The trend in the timing of peak SDD showed that the peak (equation 8) occurred 1.75 days earlier for one degree Celsius increase ($p=0.18$) in the mean annual temperature accounts for only 7.4 days of the variability in the timing of the peak SDD in the Middle Fork. The trend for the North Fork accounted for only 6 days of the variability in the timing of the peak of the SDD. A one degree Celsius increase in mean annual temperature shifted the end of SDD (equation 9) a trend estimated 1.25 ($p=0.35$) and 0.7 ($p=0.59$) days earlier in the water year for the Middle and North Fork respectively. This accounted for 5 and 3 days of the variability in the timing of the end of SDD for the Middle and North Fork.

Table 2: Results of the trend analysis for flow regime characteristics for Middle Fork and North Fork versus mean annual temperature.

	<i>Middle Fork</i>			<i>North Fork</i>		
	<i>Slope</i>	<i>SE</i>	<i>p-value</i>	<i>Slope</i>	<i>SE</i>	<i>p-value</i>
Start of SDD (day/ 1 °C)	-2.15	1.65	0.20	-1.64	1.47	0.27
Peak of SDD (day/ 1 °C)	-1.75	1.29	0.18	-1.44	1.26	0.26
End of SDD (day/ 1 °C)	-1.24	1.33	0.35	-0.72	1.33	0.59
Duration of SDD (# days/ 1 °C)	0.98	1.52	0.52	-0.092	1.30	0.94
Ascending Rate of Change (km ³ day ⁻¹ / 1 °C)	2.0x10 ⁻³	1x10 ⁻³	0.055	1.1x10 ⁻³	1.0x10 ⁻³	0.28
Descending Rate of Change (km ³ day ⁻¹ / 1 °C)	-1.9x10 ⁻³	1x10 ⁻³	0.075	1.2x10 ⁻³	1.0x10 ⁻³	0.23
Magnitude of SDD (km ³ / 1 °C)	-0.11	0.056	0.061	-0.068	0.060	0.25

The trend in the Middle Fork estimated duration of SDD (equation 10) was about one day longer for every one degree Celsius increase ($p=0.52$), and in the North Fork was one-tenth of a day earlier for every degree Celsius increase ($p=0.94$). The estimated relationship between the ascending and descending rates of change and temperature (equation 11) accounted for 27% of the variability of the rates of change for the Middle Fork and about 15% of the variability in the North Fork. The trend of the magnitude of SDD versus mean annual temperature (equation 12) ($p=0.066$) explained 26% of the variability of the magnitude of SDD for the Middle Fork. The trend in the North Fork ($p=0.25$) explained 13% of the variability in the North Fork's magnitude of SDD.

The entire suite of flow regime characteristics were significantly ($p<0.05$) related to the annual accumulation of precipitation, with the exception of the duration of SDD. The results are summarized in Table 3. The timing of the start, peak and end of SDD in the Middle Fork had a similar relationship to annual precipitation. The trend estimated that one km³ increase in annual precipitation led to a shift of the timing of the SDD between 5 and 6 day later ($p<0.01$). The timing of the start and end of SDD (equation 7 and 9) in the

North Fork was estimated to be shifted 4.5 days later in the water year for every one km³ increase in annual precipitation ($p < 0.02$). The timing of peak SDD (equation 8) had a slightly larger trend, 5.5 days later in the water year, for every one km³ increase in precipitation ($p = 0.008$) in the North Fork. Annual precipitation explained 35% of the variability in the timing characteristics of SDD in both the Middle and North Fork.

Table 3: Results of the trend analysis for flow regime characteristics for Middle Fork and North Fork versus annual precipitation.

	<i>Middle Fork</i>			<i>North Fork</i>		
	<i>Slope</i>	<i>SE</i>	<i>p-value</i>	<i>Slope</i>	<i>SE</i>	<i>p-value</i>
Start of SDD (day/ 1 km ³)	5.9	2.01	4.7x10 ⁻³	4.5	1.95	0.024
Peak of SDD (day/ 1 km ³)	5.0	1.54	1.6x10 ⁻³	4.4	1.62	8.7x10 ⁻³
End of SDD (day/ 1 km ³)	5.5	1.56	7.8x10 ⁻³	5.4	1.67	1.7x10 ⁻³
Duration of SDD (# days/ 1 km ³)	-0.65	1.97	0.52	0.65	1.78	0.71
Ascending Rate of Change (km ³ day ⁻¹ / 1 km ³)	7.2x10 ⁻³	1.1x10 ⁻³	2.7x10 ⁻¹⁰	8.2x10 ⁻³	9x10 ⁻⁴	6.4x10 ⁻¹³
Descending Rate of Change (km ³ day ⁻¹ / 1 km ³)	7.1x10 ⁻³	1.1x10 ⁻³	8.7x10 ⁻⁹	8.1x10 ⁻³	9x10 ⁻⁴	1.0x10 ⁻¹²
Magnitude of SDD (km ³ / 1 km ³)	0.39	0.052	1.9x10 ⁻¹⁰	0.48	0.054	8.6x10 ⁻¹³

The annual precipitation explained only 3% of the variability in the duration of SDD (equation 10) for both watersheds. The trend in the duration of SDD was 0.65 days shorter for every 1 km³ increase of precipitation for the Middle Fork ($p = 0.52$) and 0.65 day longer for the North Fork ($p = 0.71$). The trend in the ascending and descending rate of change (equation 11) was a about a 7×10^{-3} km³/day increase for every 1 km³ of precipitation in the Middle Fork ($p < 0.001$).

The trend in the North Fork was an increase in the ascending and descending rate of change by 8×10^{-3} for every 1 km³ accumulated (a depth of ~30cm) precipitation ($p < 0.001$). The annual precipitation accounted for 70% of the variability in the ascending rate of change in the Middle Fork and 75% for the North Fork. The annual precipitation

explained 65% of the descending rate of change variability in both the Middle and North Fork watersheds. The magnitude of SDD (equation 12) increased by 0.4 km³ and 0.5 km³ for every 1 km³ in the annual precipitation in the Middle Fork ($p < 0.001$) and North Fork respectively ($p < 0.001$). The annual precipitation accounted for about 65% of the variability in the magnitude of SDD in both watersheds for the study period.

Discussion

In order to be considered statistically different from zero, or no change, the p-values must be less than 0.05 for this study. The trends of SDD flow characteristics through time had p-values of greater than 0.10, indicating that SDD did not significantly change linearly between 1940 and 2006. Annual discharge is highly correlated with annual precipitation with a correlation coefficient of 0.85 ($p < 0.0001$). The statistical model used in this study to evaluate the changes through time 'removed' the influence of the annual discharge, and thereby some measure of annual precipitation, on changes in SDD. The assumption is made that the two major influences on the SDD flow regime are precipitation and temperature. Therefore, the model left the mean annual temperature as the major influence on changes over the study period in the watersheds.

The lack of significant trends through time may be associated with the relationship between temperature and flow regime characteristics. None of the flow regime characteristics exhibited a significant relationship with the mean annual temperature. Figure 8 shows the relationships between the mean annual temperature and several flow regime characteristics for the Middle Fork and North Fork.

The PRISM estimated mean annual temperature for the Middle and North Fork was between -6 °C and -2 °C, with a median temperature of about -4 °C. This estimate of the annual temperature included all elevations of the watersheds for the entire water year. This cool mean annual temperature may have prevented a significant relationship between temperature and SDD in the Middle and North Fork.

The time series of the start and end, the duration, the magnitude (Figure 9) graphically illustrate the high variability of SDD in the watersheds over time. The lack of apparent

change of SDD through time and with temperature may be in part due to the high natural variability of the system. Huh et al. (2005) illustrated that moderately variable hydrological data requires at least 57 years of data with half measured before the ‘disturbance’ in order to detect small trends in the discharge. While this study has 67 years of data, the flow regime in the Flathead River basin is highly variable and small trends in streamflow response climate change may be difficult to detect. The relationship between flow regime components and temperature may not be linear, as is assumed in the statistical models used in this study. This may also explain the lack of relationships found in this analysis.

The six of the seven SDD flow regime characteristics are driven by the annual accumulation of precipitation in both watersheds. Figure 10 illustrates the relationship between the start, duration, magnitude and ascending rate of change to annual precipitation. The relationship between the annual precipitation and timing of the start, peak and end of SDD shows that a decrease in precipitation leads to earlier timing characteristics (p -values < 0.01) for the Middle and North Fork watersheds. The ascending and descending rate of change also showed significant relationship with annual precipitation ($p < 0.0001$). The amount of discharge added to the streamflow each day increases as the annual precipitation increases, and the decrease in the amount of discharge on does up as the annual precipitation goes up. The magnitude of SDD increases as the annual precipitation increases. The magnitude of SDD increases as the annual precipitation increases. The duration of the SDD had no significant relationship with precipitation. Heterogeneity of the snowpack can affect the timing of snowmelt in a basin (Luce et al, 1998). The deeper snow drifts lead to snowmelt later into the season.

This is seen in the comparison of water year 2001 with the accumulated precipitation of 2.1 km^3 (depth of 67cm) and the 1954 with 5.1 km^3 (depth of 165cm) precipitation in Figure 11. The annual precipitation in 1954 was 40% greater than in 2001. The start of SDD was 5 days earlier in 2001 than in 1954, the peak of SDD was 4 days earlier. The timing of the end of SDD was 20 days earlier in 2001 than in 1954. The ascending and descending rate of change was $0.03 \text{ km}^3/\text{day}$ and $0.02 \text{ km}^3/\text{day}$ less in 2001 than in 1954. Finally, the magnitude of SDD was 1.8 km^3 less in 2001 than in 1954.

The modeled relationship between these parameters for an annual precipitation of 5 km^3 compared to an annual precipitation of 2 km^3 (40% difference) showed similar results. The start and peak of SDD in the year with 2 km^3 compared to a 5 km^3 of annual precipitation were estimated to be 13 days earlier. This is 8 and 9 days earlier than the timing in 2001. The discrepancy may be due to the large amount of variation not accounted for by the relationship between precipitation and timing of SDD. The end of SDD was estimated by the estimated relationship should have been 20 days earlier in 2001 than in 1954. The ascending and descending rate of change was modeled to be $0.02 \text{ km}^3/\text{day}$ less in the year with 2 km^3 than in the year with 5 km^3 precipitation, and the magnitude had an estimated difference of 1.44 km^3 . These estimates are very similar to actual comparison of 1954 and 2001.

The relationship between SDD and annual precipitation shows that the change in the stream discharge associated with precipitation is more complex than a simple shift in timing. This can have implications for the relationship with precipitation, SDD and ecology. A decrease in precipitation may lead to lower discharge late in the summer if the shift overcomes the lower loss of discharge per day in the descending limb of the discharge curve. This may lead to lower velocities which may prevent successful migration and spawning (Smith, 1978; Heggenes and Traaens, 1988). The shift in SDD as well as the low magnitude may increase the invasability of a stream by rainbow trout by decreasing spring discharge velocities which will decrease the mortality of the summer emergent fry (Fausch et al., 2000). Benthic algae may suffer during low precipitation

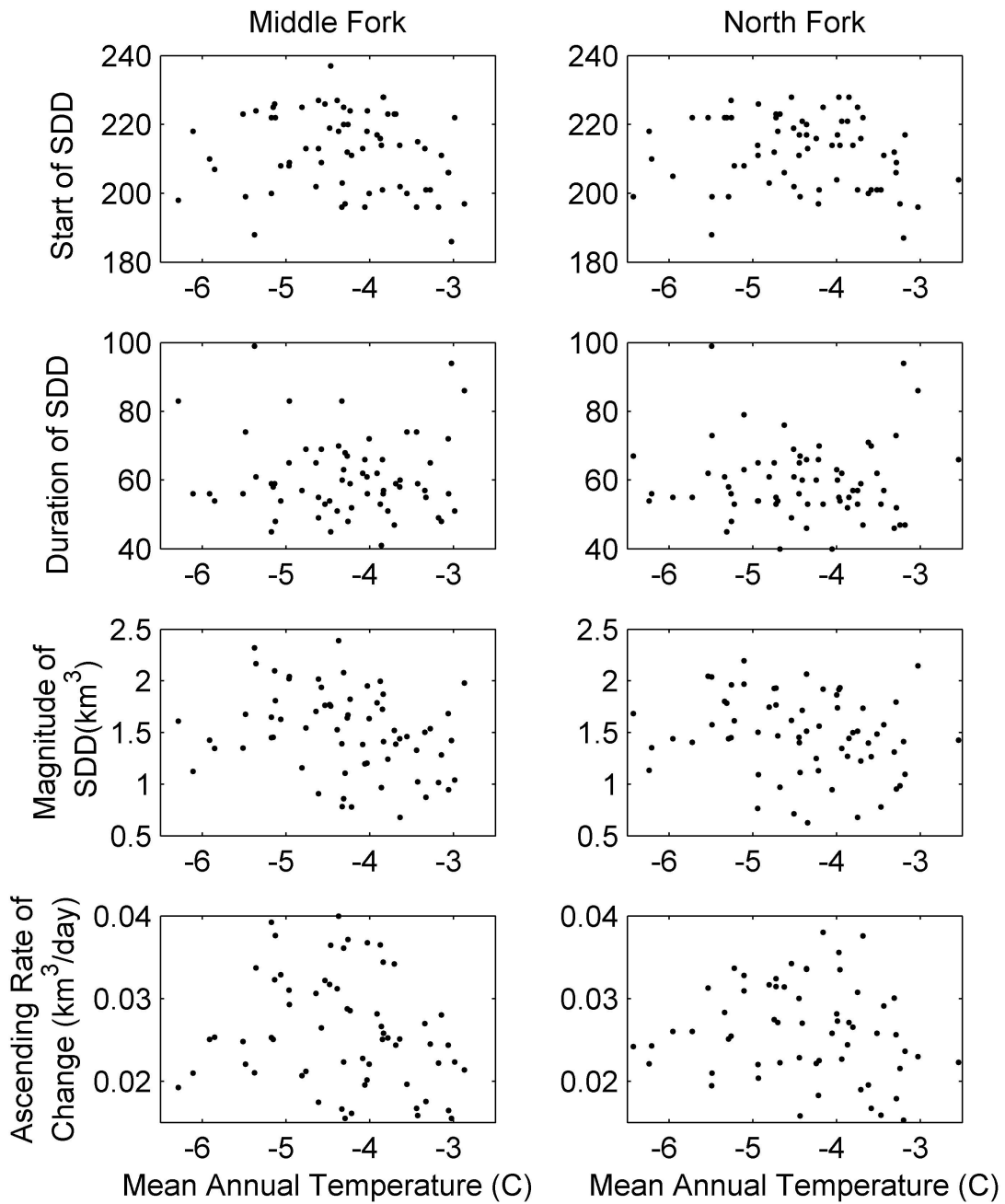


Figure 8: Flow regime components versus mean annual temperature for the Middle Fork (right) and the North Fork (left) for water year 1940 to 2006. The trend lines represent significant ($p < 0.05$) trends.

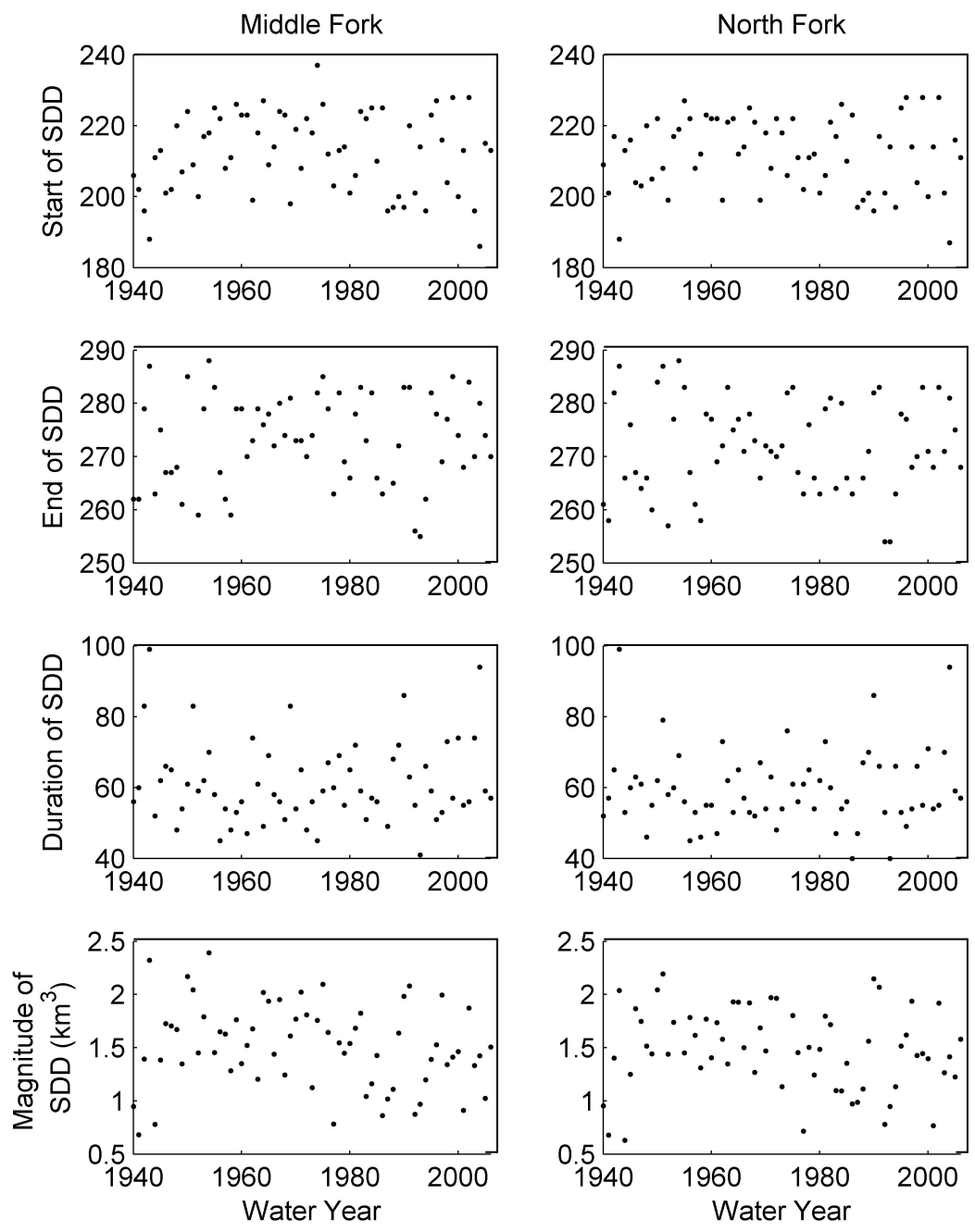


Figure 9: Time series plots for the start, end, duration, and magnitude for the Middle Fork (left) and North Fork (right). There were no significant trends in the flow regime parameters through time for either watershed.

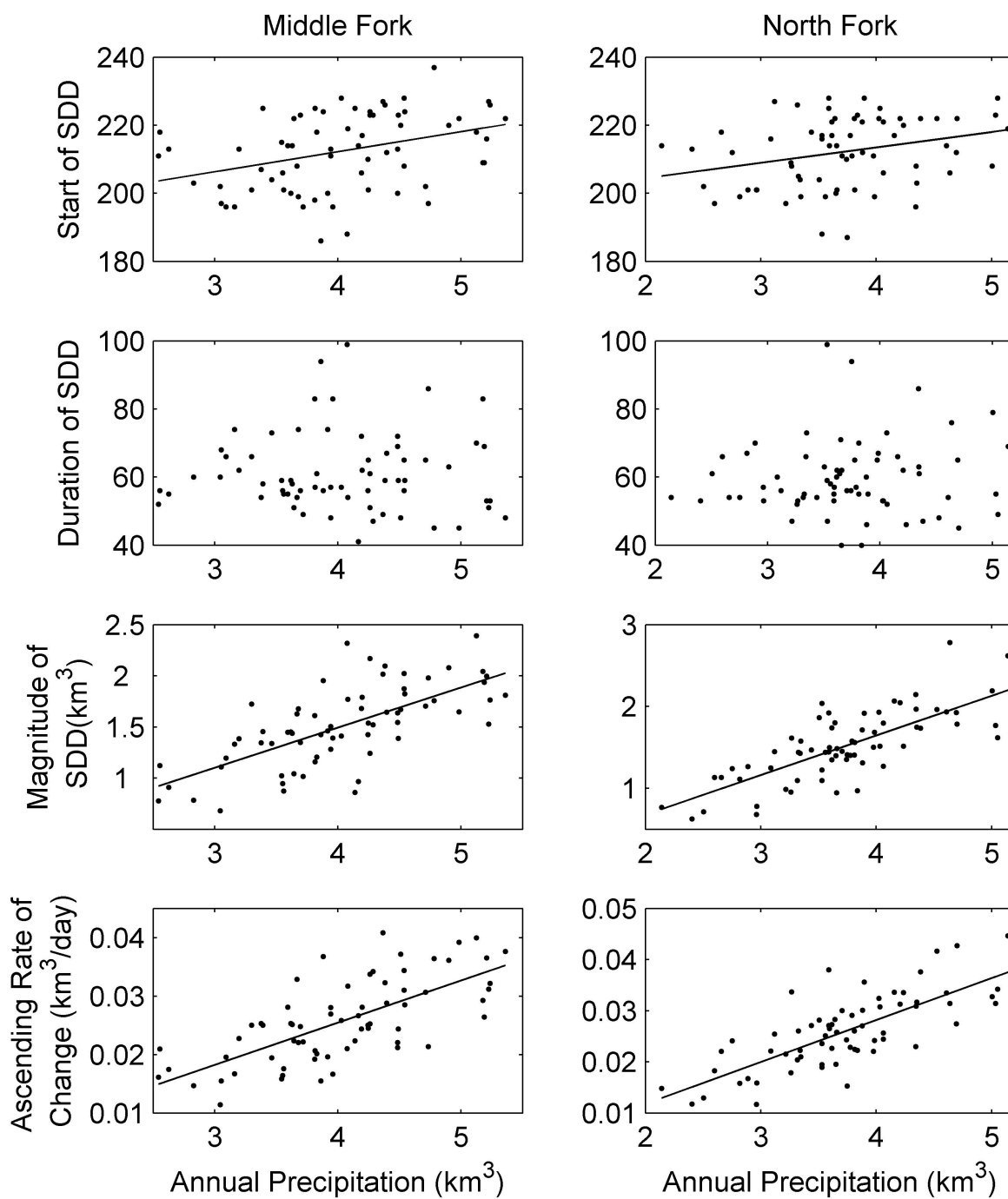


Figure 10: Flow regime components versus annual precipitation for the Middle Fork (right) and the North Fork (left) for water year 1940 to 2006. Cumulative annual precipitation of 3 km^3 is equivalent to a depth of precipitation of ~ 90 and 95 cm for the Middle and North Fork respectively. Cumulative precipitation of 5 km^3 is equivalent to a depth of precipitation of 150 and 160 cm for the Middle and North Fork. The trend lines represent significant ($p < 0.05$) trends.

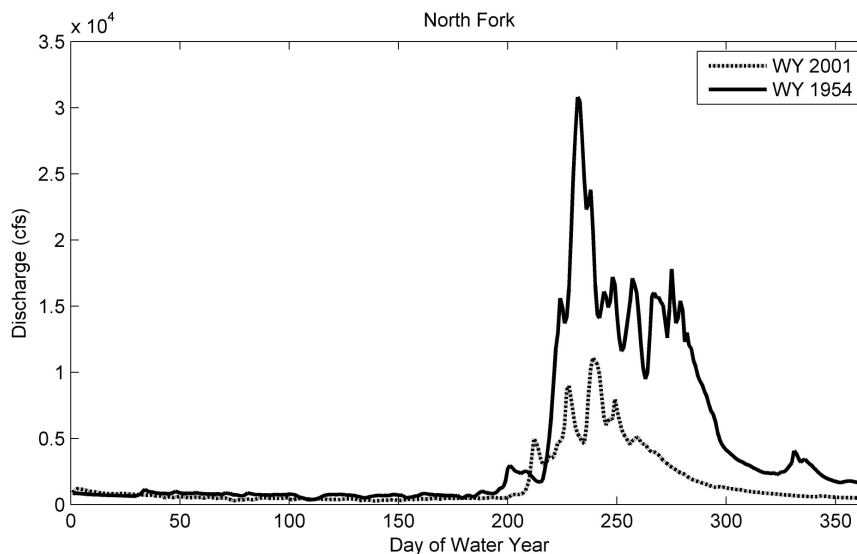


Figure 11: Discharge curves for the Middle Fork for a high precipitation year (water year 1954) and a low precipitation year (water year 2001). The flow characteristics are similar to what is predicted by the conceptual model. The timing of the low precipitation year is shifted earlier in the year, the limbs of the curve are gentler and the magnitude is smaller compared to the high precipitation year.

years. A lower SDD magnitude and a decreased rate of change may lead to a higher biomass of algae in a stream. This will increase the fecundity of the grazing macroinvertebrates. The larger hatch of insects the following year may decimate the algae population if it is another low precipitation year (Peterson et al., 2001). A low precipitation year will not affect the already established *Salix* and *Populus* individuals but the gentler rate of change may reduce the recruitment of the new seedlings (Mahoney and Rood, 1998; Wood and Cooper, 2005).

Conclusion

There is no evidence for a monotonic change in the snow-dominated discharge in the headwaters of the Flathead River basin between water year 1940 and 2006. There was no significant linear trend in any of the flow regime parameters and no significant linear trend in temperature during this time. This may be because the flow regime parameters were highly variable and this high variability may make it difficult to detect any small trend using least squares techniques (Huh et al., 2005) over this length of time. Or possibly, the high-elevation headwaters may be too cold to respond to any regional

warming suggested by previous authors. However, there were significant relationships with precipitation, with the start of SDD, magnitude, and the ascending and descending rate of change and the volume of annual precipitation. The duration, however, may not be driven by precipitation directly. It may be affected by heterogeneity in the snowpack in the watershed (Luce et al, 1998).

Annual precipitation is a driver of variation in the headwaters of the Flathead River basin. In the western United States, precipitation and snowpack is associated with natural climate oscillations, linked to Pacific Ocean sea surface temperature, such as El Nino Southern Oscillations (ENSO) or Pacific Decadal Oscillations (PDO) (Beebee and Manga, 2004; Cayan et al., 1999; McCabe and Dettinger, 2002). The variability in the SDD flow regime in the Flathead River basin may be driven by natural climate oscillations. An increase in precipitation will shift the SDD later in the year and create steeper rates of change of the ascending and descending limbs of the discharge curve of SDD. The magnitude of SDD will be increased.

This suite of parameters allows for the relative trends in critical components of the snowmelt-dominated discharge flow regime in unmodified streams. It is an efficient and relatively simple method for quantifying the timing, duration, magnitude and rate of change of SDD. These SDD flow regime characteristics can be used in water management investigations as well as investigations as to how the ecosystems interact with stream discharge in snowmelt-dominated watersheds.

The parameter developed in this study may be a tool for investigating relative changes of some flow characteristics but it may be made more sensitive to changes relative to 'baseflow' of the stream. The algorithms estimate of the start of the SDD may be slightly later than the one would subjectively estimate as the start of the SDD and a few days earlier than a subjectively estimated end. The peak, however, seems to be reasonably estimated by the algorithm. This algorithm may be improved by mathematically choosing the day where the second derivative begins to rise up, as opposed to the maximum value (figure 4c), for an estimate of the start of SDD. A better estimate of the end of SDD would be made by being able to objectively choosing the day the second derivative

begins to flatten back out again (figure 4c). It seems reasonable that attempts to define parameters in a complex system will require a much more complex algorithm.

References

- Auble, G. T., Friedman, J. M., & Scott, M. L. (1994). Relating riparian vegetation to present and future streamflows. *Ecological Applications*, 4(3), 544-554.
- Beebee, R. A., & Manga, M. (2004). Variation in the relationship between snowmelt runoff in Oregon and ENSO and PDO. *Journal of the American Water Resources Association*, 40(4), 1011-1024.
- Cayan, D. R., Kammerdiener, S. A., Dettinger, M. D., Caprio, J. M., & Peterson, D. H. (2001). Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society*, 82(3), 399-415.
- Cayan, D. R., Redmond, K. T., & Riddle, L. G. (1999). ENSO and hydrologic extremes in the western United States. *Journal of Climate*, 12(9), 2881-2893.
- Fausch, K. D., Taniguchi, Y., Nakano, S., Grossman, G. D., & Townsend, C. R. (2001). Flood disturbance regimes influence rainbow trout invasion success among five holarctic regions. *Ecological Applications*, 11(5), 1438-1455.
- Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D. W., & Medina-Elizade, M. (2006). Global temperature change. *Proceedings of the National Academy of Sciences of the United States of America*, 103(39), 14288-14293.
- Heggenes, J., & Traaen, T. (1988). Downstream migration and critical water velocities in stream channels for fry of four salmonid species. *Journal of Fish Biology*, 32(5), 717-727.
- Huh, S. H., Dickey, D. A., Meador, M. R., & Ruhl, K. E. (2005). Temporal analysis of the frequency and duration of low and high streamflow: Years of record needed to characterize streamflow variability. *Journal of Hydrology*, 310(1-4), 78-94.

- Luce, C. H., Tarboton, D. G., & Cooley, K. R. (1998). The influence of the spatial distribution of snow on basin-averaged snowmelt. *Hydrological Processes*, 12(10-11), 1671-1683.
- Mahoney, J. M., & Rood, S. B. (1998). Streamflow requirements for cottonwood seedling recruitment -an integrative model. *Wetlands*, 18(4), 634-645.
- McCabe, G. J., & Dettinger, M. D. (2002). Primary modes and predictability of year-to-year snowpack variations in the western united states from teleconnections with pacific ocean climate. *Journal of Hydrometeorology*, 3(1), 13.
- Moore, J. N., Harper, J. T., & Greenwood, M. C. (2007). Significance of trends toward earlier snowmelt runoff, Columbia and Missouri basin headwaters, western united states. *Geophysical Research Letters*, 34(16), L16402.
- Mote, P. W. (2003). Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophysical Research Letters*, 30(12), 1601.
- Mote, P. W. (2006). Climate-driven variability and trends in mountain snowpack in western North America. *Journal of Climate*, 19(23), 6209-6220.
- Olden, J. D., & Poff, N. L. (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications*, 19(2), 101-121.
- Ott, R. L., & Longnecker, M. (2001). *An introduction to statistical methods and data analysis* (Fifth ed.). Pacific Grove, CA: Duxbury.
- Peterson, C. G., Valett, H. M., & Dahm, C. N. (2001). Shifts in habitat templates for lotic microalgae linked to interannual variation in snowmelt intensity. *Limnology and Oceanography*, 46(4), 858-870.

- Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegard, K. L., Richter, B. D., et al. (1997). The natural flow regime. A paradigm for river conservation and restoration. *Bioscience*, 47(11), 769-784.
- Richter, B. D., Baumgartner, J. V., Powell, J., & Braun, D. P. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology*, 10(4), 1163-1174.
- Serreze, M. C., Clark, M. P., Armstrong, R. L., McGinnis, D. A., & Pulwarty, R. S. (1999). Characteristics of the western united states snowpack from snowpack telemetry (SNOTEL) data. *Water Resources Research*, 35(7), 2145-2160.
- Smith, A. K. (1973). Development and application of spawning velocity and depth criteria for Oregon salmon. *Transactions of the American Fisheries Society*, 102(2), 312.
- Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2005). Changes toward earlier streamflow timing across western North America. *Journal of Climate*, 18(8), 1136-1155.
- Tiku, M. L., Tan, W. Y., & Balakrishnan, N. (1986). *Robust inference*. New York: M. Dekker.
- Wilcox, R. R. (2001). *Fundamentals of modern statistical methods: Substantially improving power and accuracy*. New York, New York: Springer.
- Wilcox, R. R. (2005). *Introduction to robust estimation and hypothesis testing* (Second Edition ed.). Burlington, MA: Elsevier Academic Press.
- Woods, S. W., & Cooper, D. J. (2005). Hydrologic factors affecting initial willow seedling establishment along a subalpine stream, Colorado, U.S.A. *Arctic, Antarctic, and Alpine Research*, 37(4), 636-643.

CHAPTER 2: COMPARING THE EFFECTS OF DAM-MODIFIED AND CLIMATE CHANGE ON STREAMFLOW IN THE FLATHEAD RIVER BASIN, NORTHWESTERN MONTANA

Introduction

The snowpack of the northwestern United States provides large amounts of water storage during the winter. In the spring, the water is released and much of it is captured in reservoirs and released later in the year for agriculture, hydroelectric power generation, or municipal uses. Payne et al. (2004) projected that the effects of climate change in the Columbia River basin will eventually lead to a reduced capacity for hydroelectric dams to meet power needs in the future because of changes in amount and timing of snow-melt runoff. Barnett et al. (2005) reports that the current reservoir storage is insufficient to handle the climate model projected shifts in river discharge by 2050. Suggestions that climate change may affect water availability are likely to lead toward a push to increase the reservoir storage capacities in the western United States as it has in California. The California Department of Water Resources has proposed two large dams over concerns of global climate change and its effects on snowmelt timing (Boxall, 2007). More rivers of northwestern United States may soon be under pressure from reservoir operations and climates change.

Previous workers have attempted to quantify how dam operations influence the streamflow of a river. Dam operations have been shown to result in lower and shorter duration peaks in discharge (Singer, 2007), and higher low flows (Magillian and Nislow, 2005; Graf, 2006; Singer, 2007). There is also a shift in the high and low extreme flows in dammed rivers (Magillian and Nislow, 2005; Graf, 2006; Lajoie et al, 2007), and reduced annual variability (Graf, 2006). Along with direct modification, snowmelt-dominated streams may be altered by global climate change. The mean global temperature increase of 0.8°C (Hansen et al., 2006) may decrease snowpack in the western United States. Several researchers have reported trends indicating an earlier

snowmelt season, due to increased mean temperature, has been occurring since the 1940's in the western United States (Cayan et al., 2001; Mote, 2003 and 2006; Stewart et al., 2005). Moore et al. (2007) used a rigorous method of data selection and a more robust measure of timing – quantiles of flow. They reported that the timing of streamflow in the Missouri and Columbia River basins were significantly related to the annual discharge. They suggested that annual precipitation, and therefore natural climate oscillations, may influence the timing of streamflow.

The three upper watersheds of the Flathead River have continuous daily stream gage records beginning in 1 October 1939. The Flathead River basin drains the relatively pristine, high-mountain watersheds of the Waterton-Glacier International Peace Park, the Bob Marshall Wilderness and the Flathead National Forest (Figure 12). The basin is an ideal region to compare direct and indirect human modifications on the characteristics of discharge in snowmelt dominated watersheds.

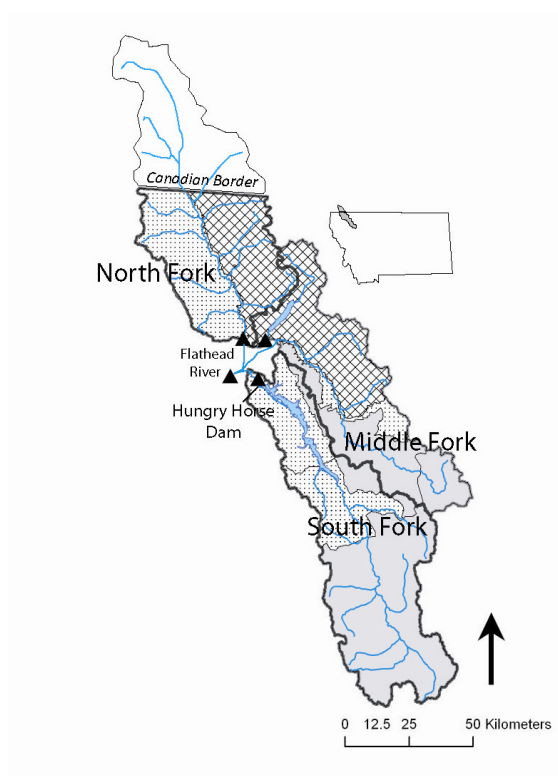


Figure 12: The Flathead River Basin in northwestern Montana with the headwater watersheds delineated and the Hungry Horse Dam is shown. The triangles mark the location of the stream gages used in this study. Wilderness areas (grey), the Flathead National Forest (dots) and the American Waterton-Glacier International Peace Park (hashes) are shown.

The flows in the Middle Fork and North Fork of the Flathead River are relatively unmodified by humans and provide an excellent opportunity to investigate global climate change on the streamflow. The Hungry Horse dam, a large hydroelectric reservoir, was completed on the South Fork of the Flathead River in 1953 in the lower end of the basin with unmodified headwaters. This makes it ideal for studying the effects of dam operations compared to climate change influence on streamflow characteristics over the last c.a. 55 years. The streamflow alterations associated with dam operations to those associated with climate change will be compared. The variance of the directly modified South Fork and natural-flow North Fork and Middle Fork is compared to examine the interannual variability created by dam operations and climate change. The stream gage downstream of the confluence of these three forks of the Flathead River has no additional tributaries or withdraws between the confluence of the three branches and the main branch Flathead River gage. It is included in this study to investigate how the operations of the Hungry Horse dam influence the characteristics of stream flow downstream after the addition of un-regulated tributaries.

Datasets

US Geological Survey (<http://waterdata.usgs.gov>) daily hydrological data from four rivers, during the interval from October 1, 1939 to September 30, 2006 were used for this study: 1) the Middle Fork Flathead River near West Glacier, Montana (12358500); 2) the North Fork Flathead River near Columbia Falls, Montana (12355500); 3) the South Fork Flathead River near Columbia Falls, Montana(12362500); 4) the Flathead River at Columbia Falls, Montana (12363000). There was relatively little (less than 30 days) data missing in the stream gage records. An estimate of the value of the occasional missing daily measurements was linearly interpolated using the measurements from the day before and after the missing data.

Parameter Development

While the previous work has focused on the modification of stream flow variables by either dams or climate change, little has been done comparing the two modes of

streamflow modification. This is often difficult because the variables used to study dam modified-streamflow may not fully describe the characteristics of unmodified streamflow. Measures estimating snowmelt-influenced discharge or peak of spring discharge have very little meaning in dammed streams. The model of an undammed snow-dominated stream begins with low flows through the fall and winter. The discharge ramps up in the spring as a result of snowmelt. In the late summer the discharge is at low flow once again. This difference can be seen in the mean daily discharge averaged over the water years 1954 to 2006 (Figure 13).

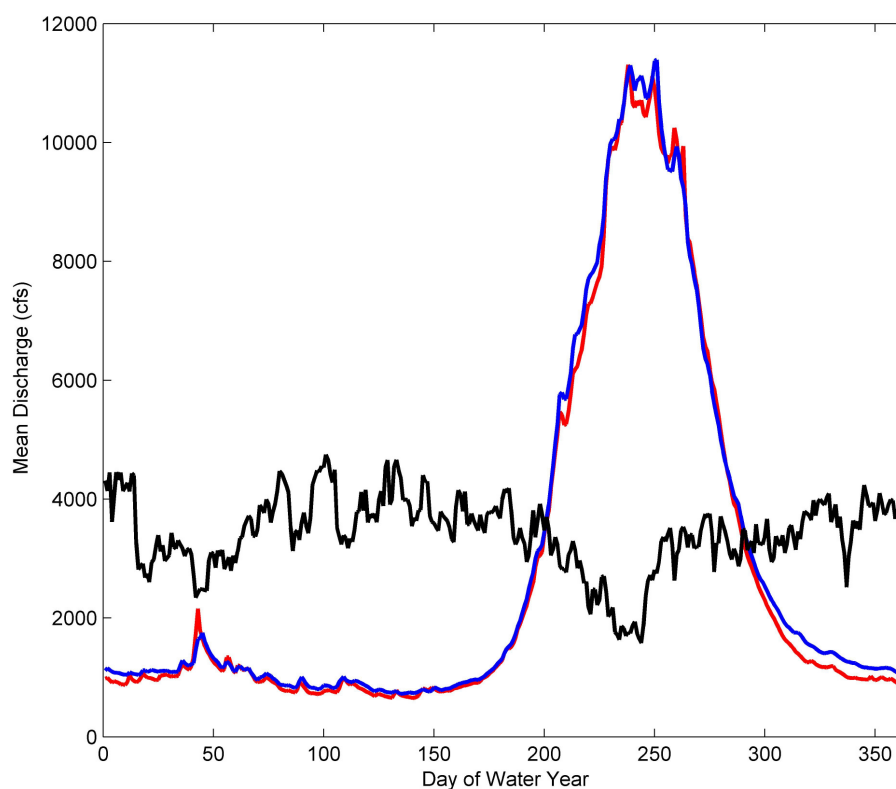


Figure 13: Mean daily discharge averaged from 1954 to 2006 for the Middle Fork (red), North Fork (blue) and the South Fork (black) of the Flathead River.

Olden and Poff (2003) discussed the usefulness of a suite of hydrologic variables developed to quantify dam influence on streamflow. They found that the variables should be used in conjunction with intuitive parameters for the problem that is being studied. The intuitive parameter in this study will be quantiles of flow. They have an intuitive and useful meaning for water management and are more robust than measures like the mean

daily or monthly flow. Quantiles of flow represent what percentage of flow has already passed the stream gage. For instance, the day of the 50th quantile of flow indicates the day of the year that half of the discharge had occurred. This is of interest to water managers who are responsible for operating the reservoirs effectively.

Using quantiles as a yearly summary variable leads to a robust variable for analysis. Quantiles of flow are not significantly affected by outliers (Wilcox, 2001). Quantiles of flow also allow for the comparison among streams and years that have dissimilar flows. This hydrologic metric was used to compare the characteristics of flow in dammed and un-dammed streams in a paired-basin study in the Flathead River basin. The cumulative percentage of discharge for the annual water year (01 October to 30 September) was calculated from the discharge records of all four stream gages. The day of the 25th, 50th and 75th quantile of flow were determined from the cumulative percentage of the discharge. The day of the 25th, 50th, and 75th quantile of flow were used to represent the early, median, and late timing components of the annual discharge (Moore et al. 2007). The cumulative percentage is bound at zero for the first day of the year and at 100 for the last day of the year, the quantiles too close to the beginning or end of the year may be biased by the boundary conditions. The number of days between the day of the 25th and 75th quantile of flow was used to estimate the interquantile duration of flow. The median flow discharge (km³/day) was the volume of flow between the 45th and 55th quantile of flow divided by the number of days between the 45th and 55th quantile of flow. The interquantile magnitude (km³) of flow was the total discharge that occurs between the day of the 25th and 75th quantile of flow.

Statistical Analysis

The annual water year (01 October to 30 September) flow characteristic time series trends were calculated for all of the streamflow variables of each of the four stream gages. A robust regression technique used bisquares weighting function in the trend analysis, which was implemented using weighted least squares. The power of this robust regression method is not significantly affected by non-normally distributed errors or inconsistent variance (heteroscedacity) (Tiku et al., 1986), which are common in

hydrological data. A trend analysis on the post-dam data (water year 1954 to 2006) was done to compare the effects of climate change and dam alterations. The simple linear statistical model used was $y = b_0 + b_1x_1$. Where y is the streamflow characteristics and x_1 is the water year.

A correlation analysis was done to compare the variance between pre-dam (1940 to 1952) and post-dam (1954 to 2006) streamflow characteristics. The correlation method was also used to estimate the effect of the Hungry Horse dam on the main branch of the Flathead River. The correlation coefficient was decided to be the median of 1000 bootstrapped Pearson's correlation analyses on the North Fork or Middle Fork compared to the South Forks pre-dam flow characteristics (Wilcox, 2005). Bootstrapping, with replacement, is a statistical technique in which the data are randomly selected to develop a new dataset. The statistical analysis, Pearson's correlation analysis in this case, is performed on the 'developed' dataset. The solutions were stored and the procedure was done 1000 times. The median of the results was used to represent the correlation between the actual datasets. This technique is used to make Pearson's correlation analysis less sensitive to non-normality and non-constant variance. This method assumes no autocorrelation is present. Autocorrelation is not notably present in the parameters in this study.

The median absolute deviation (MAD), a robust method, was used to describe the variance of the post-dam streamflow characteristics. MAD has a finite breakdown point of 0.5, meaning that it takes 50% of the data to be outliers before the MAD value is adversely affected (Wilcox, 2001). The standard errors of coefficients (SE) of the regression analysis are reported in the tables of results for completeness. The SE reported is a measure of variability of the slope coefficient as estimated by the weighted least squares method.

Results

The squared correlation coefficient estimates the variance in common between two variables. The North Fork and the Middle Fork had over 62% of the variance in common for the day of the 25th quantile of flow during the pre-dam record ($p < 0.0001$). The three rivers had about 90% of the variance for the day of the 50th and 75th quantile of flow in

common ($p < 0.0001$). The correlation coefficient comparing the Middle Fork and North Fork with the South Fork for the pre-dam interquantile duration was 0.76 and 0.72 respectively ($p < 0.0001$). The Middle Fork had 80% of its variance in the median flow discharge in common with the South Fork ($p < 0.000$). The North Fork shared 60% of the variance of the median flow discharge with the South Fork ($p = 0.003$). The correlation of the interquantile discharge of flow showed that the Middle Fork shared 80% of its variance with the South Fork, and the North Fork shares 70% of its variance ($p < 0.0001$) in the pre-dam record.

The results of the linear trend analysis of the South (dammed), North (un-dammed) and Middle (un-dammed) Fork are given in Table 4. The trends for the timing of the 25th quantile of flow for the dammed stream was opposite in sign, but had similar magnitude, compared to the un-dammed streams. Only the North Fork had a significant trend in the timing of the 25th quantile of flow. The un-dammed streams had a trend indicating that the timing of the 50th quantile of flow was 1.7 days earlier every decade. Whereas, the dammed stream showed a trend of being 13 days later every decade. All of the trends in the timing of the 50th quantile of flow were significant. The timing of the 75th quantile of flow had similar results. The trend in timing of the 75th quantile of flow for the un-dammed rivers was 5% of the trend in the dammed rivers. Only the dammed stream had a significant trend in the 75th quantile of flow. The trend in the dammed stream for the interquantile duration was 2 and 4 times larger than the trends in the North Fork and Middle Fork respectively. The median flow discharge had similar trends for the dammed and un-dammed streams. The trend in the dammed stream was not significant, however. The trend in the interquantile discharge was also similar for the dammed and un-dammed streams. Only the trend in interquantile discharge for the North Fork was not significant.

The variance, median and range of the flow characteristic estimates are given in Table 5. Figure 14 visually illustrates the magnitude of variance of the timing of the quantiles of flow for the three rivers. The variance of the timing of the 25th quantile of flow of the un-dammed streams is about 50% of the variance of the dammed stream. The median day of the 25th quantile of flow is 4 months earlier in the dammed river than in the undammed

Table 4: Results of the trend analysis for flow characteristics of the dammed and un-dammed streams versus water year for water year from 1954 to 2006.

	Middle Fork			North Fork			South Fork		
	Slope	SE	p-value	Slope	SE	p-value	Slope	SE	p-value
Timing of 25 th Quantile (day/year)	-0.20	0.12	0.097	-0.31	0.10	0.0046	0.47	0.30	0.13
Timing of 50 th Quantile (day/year)	-0.17	0.070	0.017	-0.17	0.066	0.012	1.3	0.0004	0.0012
Timing of 75 th Quantile (day/year)	-0.063	0.061	0.31	-0.059	0.062	0.35	1.4	0.35	0.00029
Interquantile Duration (# days/year)	0.147	0.11	0.17	0.26	0.095	0.0077	0.6	0.46	0.19
Median Flow Discharge (km ³ /year)	-0.00030	0.0001	0.0073	-0.00040	0.0001	0.0014	-0.0001	0.0001	0.11
Interquantile Discharge (km ³ /year)	-0.0054	0.024	0.032	-0.0048	0.0026	0.073	-0.0076	0.003	0.013

river. The range of the timing of the 25th quantile of flow is 2 times greater for the dammed stream than for the un-dammed stream. The variance of the timing of the 50th quantile of flow is 6 times greater for the dammed stream than for the un-dammed streams. The median day of the 50th quantile of flow is 2.5 months earlier in the dammed stream. The range of the timing of the 50th quantile of flow is 6.5 times greater for the dammed stream than for the undammed streams. The variance of the timing of the 75th quantile of flow of the dammed stream is 6 times greater than the variance in the Middle Fork, and 7 times greater than the North Fork. The median day of the 75th quantile of flow was similar for all three streams. The range for the dammed stream was 6.5 times greater than in the undammed streams.

Figure 15 illustrates the variance in the duration, median flow discharge and interquantile discharge for the three rivers. The variance of the interquantile duration for the South Fork is more than 2 times greater than the variance of the un-dammed streams. The median interquantile duration was 3 times greater for the dammed streams than for the undammed streams. The range of the interquantile duration for the Middle and North Fork was 75% and 50% of the range of the South Fork. The variance for the median flow discharge of the dammed streams is 55% of the un-dammed rivers. The median value of the median flow discharge for the dammed stream is 40% undammed streams. The range of the median flow discharge of the Middle Fork is 1.5 times greater than the South Fork. The range of the median flow discharge of the North Fork is 4.3 times the range of the dammed stream. The median interquantile discharge was similar between the dammed and un-dammed streams, 1.6km³ and 1.3 km³ respectively. The variance of the interquantile discharge was also similar between the three streams. The MAD was 0.3 for the dammed stream and 0.2 for the undammed streams.

Table 5: Descriptive statistics for the South, North and Middle Fork of the Flathead River from 1954 to 2006. The comparison of these statistics is based on the water year, where day 1 of the year is 01 October.

		South Fork	North Fork	Middle Fork
Timing of 25 th Quantile	median	30-Dec	2-May	1-May
	min	6-Nov	2-Mar	6-Mar
	max	13-Apr	19-May	28-May
	MAD	27.1	11.7	15.0
Timing of 50 th Quantile	median	13-Mar	27-May	27-May
	min	6-Dec	9-May	8-May
	max	19-Jul	11-Jun	11-Jun
	MAD	36.1	6.0	6.4
Timing of 75 th Quantile	median	17-Jun	20-Jun	19-Jun
	min	15-Feb	6-Jun	5-Jun
	max	1-Sep	5-Jul	2-Jul
	MAD	39.2	5.6	6.4
Interquantile Duration (# of days)	median	156	52	52
	min	75	35	33
	max	225	107	143
	MAD	40	10.1	14
Median Flow Discharge (km ³)	median	0.014	0.035	0.036
	min	0.0023	0.014	0.012
	max	0.044	0.075	0.20
	MAD	0.0070	0.011	0.013

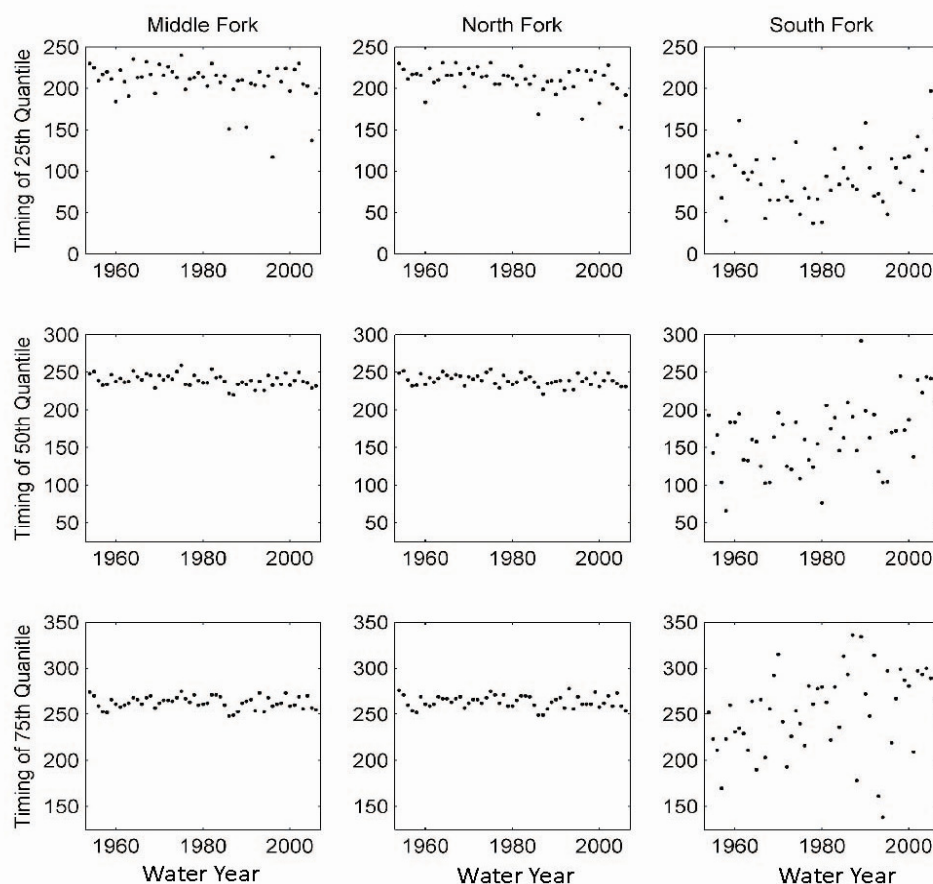


Figure 14: Time series plots for the timing characteristics of flow for the Middle Fork (left) and North Fork (center) and the South Fork (right). The same scales were used to illustrate the range of variance of each stream.

The results of the correlation analysis comparing the Middle, North and South Fork to the Flathead River for the pre-dam and post-dam records are given in Table 6 and Table 7. Pre-dam (water year 1940 to 1952) the Flathead River had over 80% of the variance in the timing of the 25th quantile of flow in common with the North, Middle and South Fork ($p < 0.0001$). The Flathead River had over 90% variance of the timing of the 50th and 75th quantiles of flow in common with the Middle, North and South Forks. The interquantile duration of the Flathead River shared over 80% of its variance with the other three streams pre-dam. The median flow discharge of the Flathead River shared between 85% and 95% of its variance with the other three streams. The interquantile magnitude of flow for the Flathead River had between 90% and 97% variance in common with the Middle,

North and South Forks for the pre-dam record. All of the correlation coefficients for the flow characteristics were significant for the pre-dam record.

The post-dam record was from water year 1953 to 2006. The correlation coefficient comparing the Flathead River and the un-dammed rivers for the post-dam timing of the 25th quantile of flow were not significant. The correlation between timing of the 25th quantile of flow for the Flathead River and the dammed stream was significant.

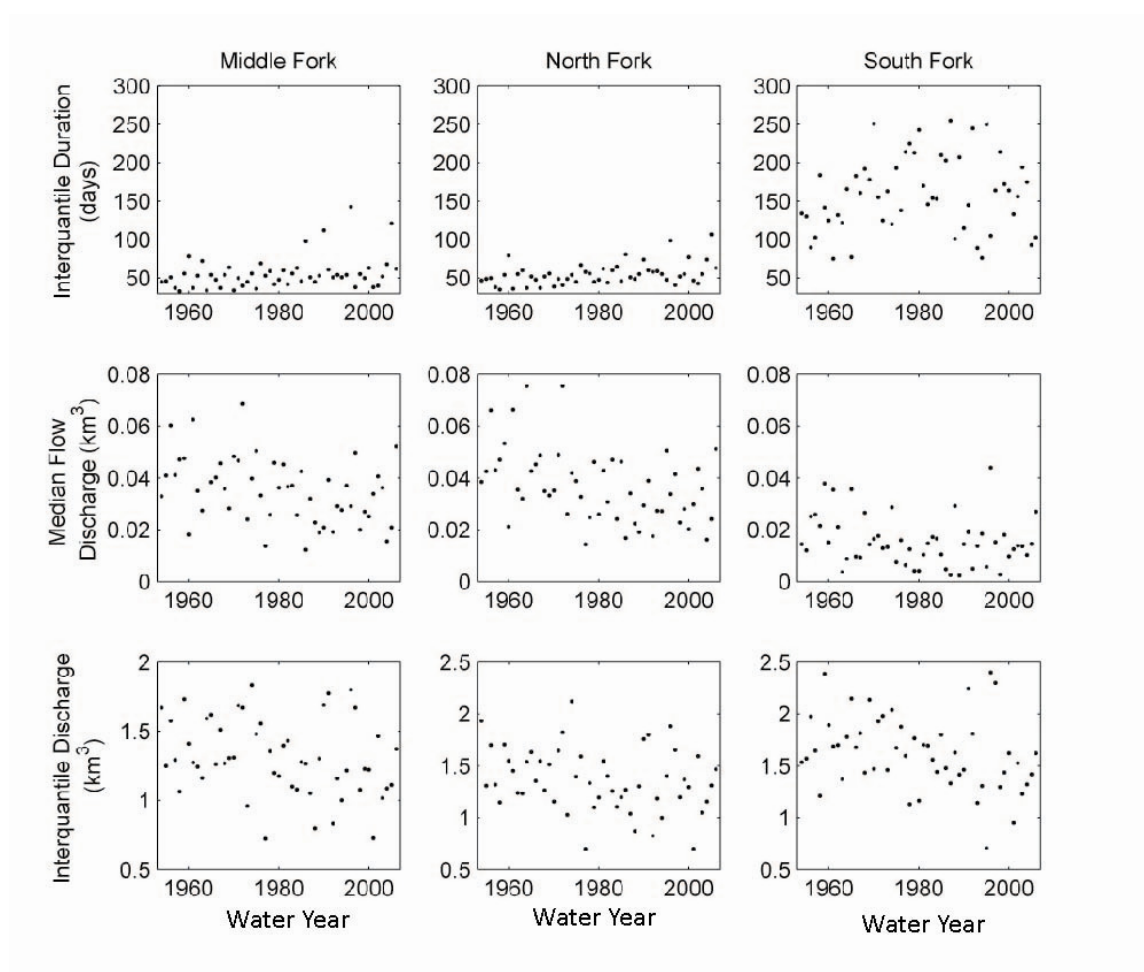


Figure 15: Time series plots for the interquantile duration, median flow and interquantile discharge of flow for the Middle Fork (left) and North Fork (center) and the South Fork (right). The same scales were used to illustrate the range of variance of each stream.

Table 6: Results from correlation analysis comparing the timing of flow characteristics of the Flathead River and the Middle, North and South Fork for the pre-dam (1940 to 1952) and the post-dam (1954-2006) study periods.

	Flathead River versus:	Timing of 25 th (day of water year)	p-value	Timing of 50 th (day of water year)	p-value	Timing of 75 th (day of water year)	p-value
Pre-dam	Middle Fork	0.96	<0.0001	0.99	0.0004	0.97	0.0028
	North Fork	0.94	<0.0001	0.98	0.0082	0.97	0.0093
	South Fork	0.89	<0.0001	0.99	0.0002	0.97	0.0023
Post-dam	Middle Fork	0.21	0.12	0.68	<0.0001	0.51	0.0001
	North Fork	0.26	0.058	0.66	<0.0001	0.47	0.0003
	South Fork	0.43	0.0011	0.16	0.24	0.63	<0.0001

Table 7: Results from correlation analysis comparing the interquantile duration, median flow, and interquantile discharge of the Flathead River and the Middle, North and South Fork for the pre-dam (1940 to 1952) and the post-dam (1954-2006) study periods.

	Flathead River versus:	Interquantile duration (# of days)	p-value	Median Flow Discharge (km ³)	p-value	Interquantile Discharge (km ³)	p-value
Pre-dam	Middle Fork	0.9632	<0.0001	0.9769	<0.0001	0.9852	<0.0001
	North Fork	0.9282	<0.0001	0.921	<0.0001	0.9612	0.0002
	South Fork	0.8729	<0.0001	0.9432	<0.0001	0.9471	0.0009
Post-dam	Middle Fork	0.1085	<0.0001	0.443	0.0008	0.9203	0.0271
	North Fork	0.146	<0.0001	0.5545	<0.0001	0.9062	0.0489
	South Fork	0.1777	0.2358	0.0737	0.5966	0.8201	0.9991

The Flathead and the South Fork shared 19% of the variance, 23% of the pre-dam correlation, of the timing of the 25th quantile of flow. The shared variance for the Middle and North Fork versus the Flathead River was only 5% of the pre-dam correlation. The

variance of the timing of the 50th quantile of flow for the Flathead River was ~45% in common with the undammed streams. The correlation coefficient for the timing of the 50th quantile of flow of the South Fork versus the Flathead River was not significant. The Middle and North Fork shared only 45% of the pre-dam common variance of the timing of the 50th quantile of flow with the Flathead River. The variance shared by the Flathead River and the Middle, North and South Fork for the timing of the 75th quantile of flow was 25%, 22% and 39% respectively. This was 27%, 25%, and 40% of the shared variance pre-dam.

The correlation coefficient for the comparison of the Flathead River and the undammed streams is significant for the interquantile duration. The variance shared between the Flathead River and the un-dammed streams is rather low, less than 2%. This was less than 5% of the variance in common in the pre-dam data. The median flow discharge of the Flathead River shared only 20% of its variance with the Middle Fork. This is 20% of the variance shared between the Flathead River and the Middle Fork pre-dam. The shared variance between the Flathead River and the North Fork was 30%. This was 36% of the variance in common pre-dam. The South Fork was not significantly correlated with the Flathead River for this flow characteristic with a correlation coefficient of 0.005. This is about 0.5% of the variance in common between the Flathead River and the South Fork in the pre-dam data.

Discussion

The paired-basin technique allows for the direct comparison of climate change alterations to flow and the dam operation alteration of streamflow characteristics. This method assumes that the basins have similar characteristics and will behave in a similar manner to a given set of conditions. In this case, if the South Fork flow characteristics were correlated to the Middle Fork and North Fork pre-dam, they should have continued to have correlated if the Hungry Horse dam was not built. Snowmelt runoff tends to show a regionally cohesive pattern of discharge timing and magnitude as a result of atmospheric circulation in the western United States (Peterson et al., 2000). The forcing for this regional organization may be temperature. The previous chapter in this thesis illustrates

that the main forcing for variability in the headwaters of the Flathead River basin is precipitation. For this reason, a correlation analysis was done to determine if there is a relationship in the variability between the three watersheds.

The analysis of the three rivers during the pre-dam record shows that there was at least a 55% commonality for the flow characteristics between the variance of the South Fork and the other two rivers. The timing characteristics are well correlated with over 62% of the variance being in common between South Fork and the Middle Fork or the North Fork ($p < 0.05$). The basins are well correlated considering the small sample size of 12 years. A paired-basin study seems appropriate in the headwaters of the Flathead River basin keeping in mind the relationships between the pre-dam watersheds.

A trend of all three rivers implied that the total volume of discharge between the 25th and 75th quantile of flow has decreased since 1954 (Figure 16). This decrease is possibly related to Pacific Decadal Oscillations (PDO) shift from a cool phase beginning in the mid-1940's to the current warm phase in mid-1970's. The cool PDO phase is associated with increased snowpack in the Pacific Northwest, whereas the warm phase means warmer drier winter (McCabe and Dettinger, 2002). The trend toward a decrease in interquartile flow is consistent with the shift in phases of PDO in the northwestern United States.

The undammed streams had a trend implying a shift toward earlier timing of the quantiles of flow. Figure 17 shows the trends in the interquartile duration and magnitude, as well as the median flow discharge for 1954 through 2006. Moore et al. (2007) reported a positive relationship between timing of quantiles of flow and annual discharge. Meaning that a decrease in annual discharge will lead to an earlier timing of the quantile of flow. The Middle and North Fork trends are consistent with this hypothesis. The trends in the un-dammed streams showed a shift toward an earlier timing of the quantiles of flow. This is associated by a decrease in the median flow discharge and interquartile discharge. The annual discharge for the un-dammed streams had a trend of 0.01 km³ decrease per year over the post-dam study period ($p = 0.09$). The timing of the quantile of flow for the dammed stream is not behaving in a manner consistent with Moore et al. (2007)

hypothesis. The timing of the quantiles of flow is shifting later in the water year. This despite a significant trend ($p = 0.02$) showing a decrease in annual discharge in the South Fork.

The median flow discharge trend estimated a decrease of 0.016 km^3 , 5% of the median value, over the study period for the undammed streams. The trend of the dammed river implied a decrease of 0.0054 km^3 , 40% of the median value, over the post-dam study period. The dammed stream had a trend that indicated a shift in the timing of the quantiles of flow later in the water year. The trend implied shift in the timing of the 25th quantile of flow was 25 days later. The trend in the dammed stream suggested a shift in the timing of the 50th and 75th quantile of 73 days later over the post-dam study period.

The interannual variability of the timing of the quantile of flow was between 2 and 3 times greater for the dammed stream than for the undammed streams. Dam operations have also increased the variance of the interquantile duration. The greater variability of flow in the dammed river may have been in part due to the modification of the augmented flow regimes beginning in the 1980's (Bureau of Reclamation, 2002). The dam operations reduced the median flow variability compared to the undammed streams. This measure indicates that there was much less interannual variability within the flow between the 25th and 75th quantile of flow.

Post-dam these relationships are altered by the dam operation-induced alterations to the South Fork flow characteristics. The changes in the shared variance between the Flathead River and the three headwater streams indicate that the South Fork is dominating the stream flow early in the water year. Post-dam, the day of the 25th quantile of flow on the Flathead River is only significantly correlated with the South Fork flow from 1954 to 2006.

The spring peak flows of the unmodified rivers overwhelm the major influence of the dam. The South Fork River still reduces the variance in common between the Flathead River and the Middle and North Fork Rivers. The correlation coefficients denote a less common variance between the Flathead River and the Middle and North Fork. The day of

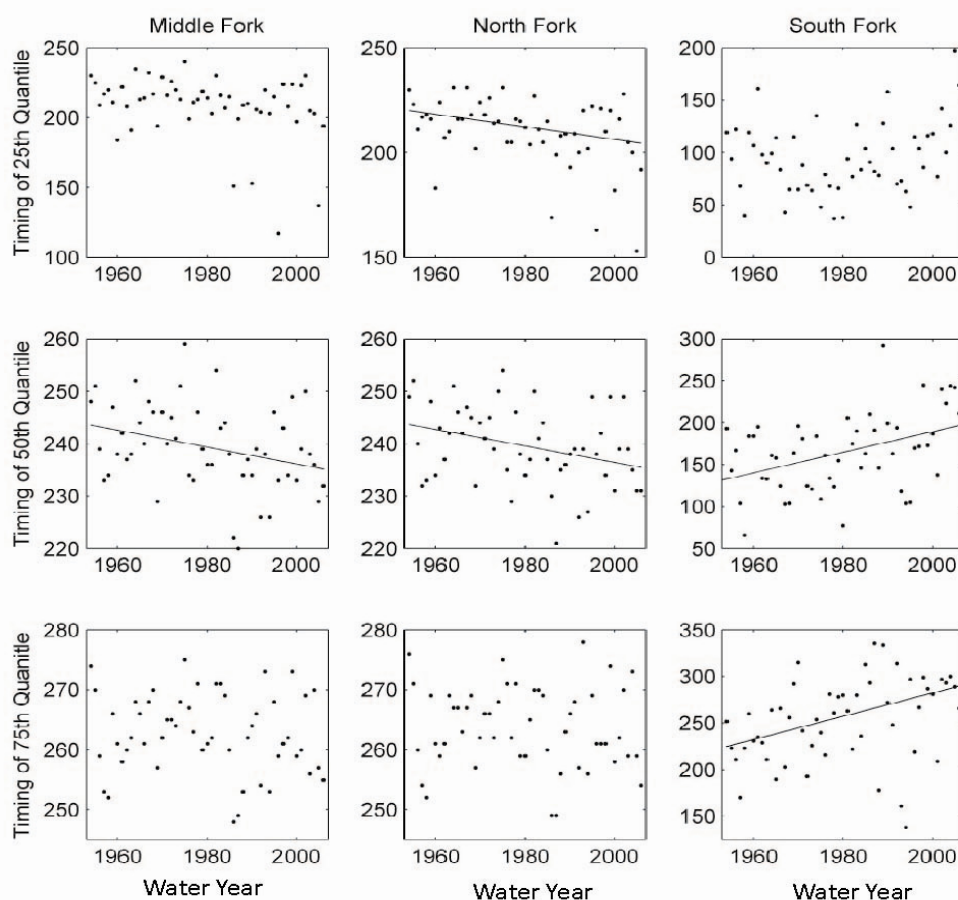


Figure 16: Time series plots for the timing characteristics of flow for the Middle Fork (left) and North Fork (center) and the South Fork (right). Significant trends ($p < 0.05$) are indicated by trend lines.

the 50th quantile of flow for the Flathead River shares only half of the variance it had in common with the two unmodified rivers pre-dam. The South Fork is not significantly correlated to the Flathead River for the timing of the 50th quantile of flow. The later flow is significantly related to all three headwater streams, but the influence of the South Fork is still present in the form of reduced correlation coefficients. The common variance for the day of the 75th quantile of flow is 25% between the Flathead River and the unmodified Rivers. Post-dam, the South Fork shares 30% of its variance with the Flathead River compared to the pre-dam r^2 of 0.75. The interquantile duration of flow showed the same reduction in the correlation coefficients.

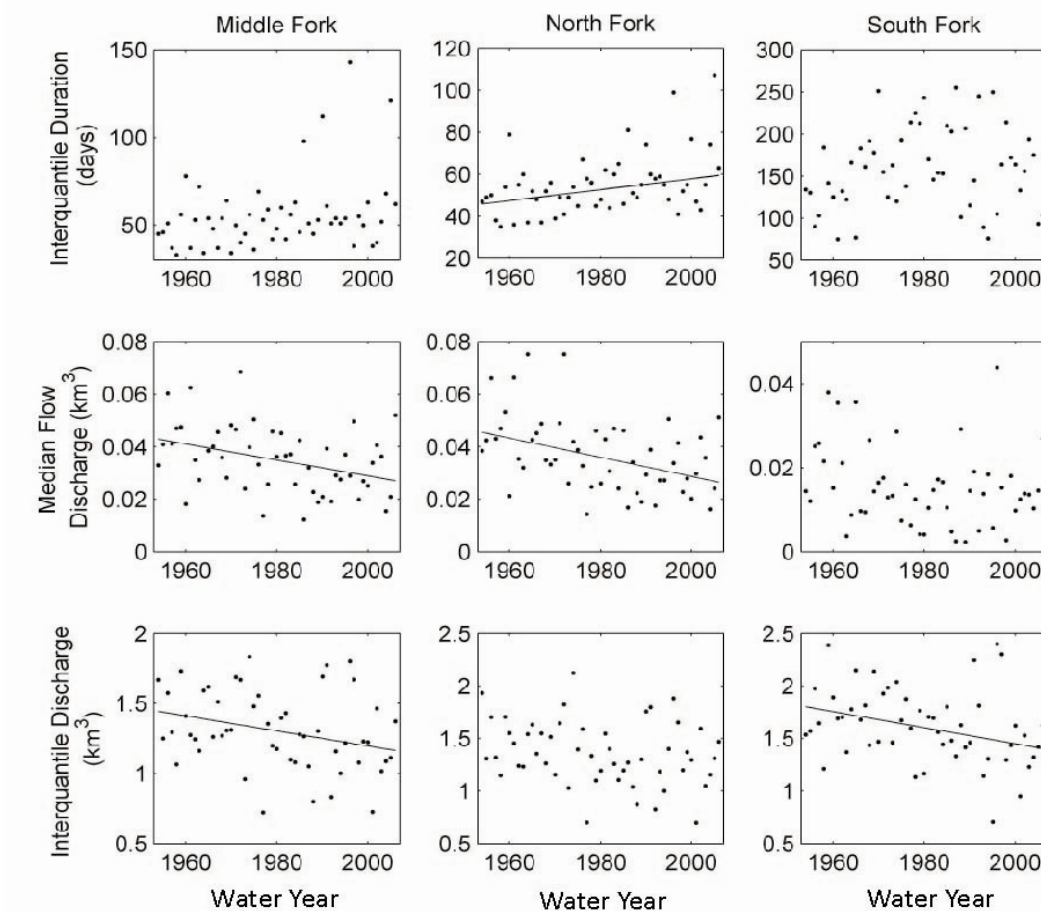


Figure 17: Time series plots for the interquantile duration, median flow and interquantile discharge for the Middle Fork (left) and North Fork (center) and the South Fork (right). Significant trends ($p < 0.05$) are illustrated with trend lines.

Conclusion

The operation of the Hungry Horse dam on the South Fork produced trends in the timing of the quantiles that were significantly different than the trends seen in the un-dammed streams. The trends for the dammed stream for the timing were larger in magnitude and opposite in sign compared to the un-dammed streams. The un-dammed streams show trends that are consistent with the hypothesis that streamflow timing is related to annual discharge. A decrease in annual discharge is associated with a shift in the timing earlier in the water year. This relationship is just the opposite in the dammed stream. The decreasing trend, seen in all three streams, in the interannual magnitude of flow may be

related to natural climate oscillations. The post-dam study period begins in a cool PDO phase and ends in a warm PDO phase. This indicates that the beginning of the study period was wetter and cooler than the end of the study period.

The interannual variance of the flow characteristics was increased by up to 7 times by the Hungry Horse dam operations on the South Fork. The dammed stream showed a greater variance in all of the flow characteristics except the median flow discharge. The adjustments made to the flow augmentation regimes since the 1980's implemented for the Hungry Horse dam may be responsible for the large interannual variance. Graf (2006) reported that the daily variability of the flow in dammed rivers is reduced. This is seen in the South Fork. The smaller variance of the median flow discharge in the dammed river implies there was less variance within the interquartile of flow from year to year.

The South Fork appears to influence all of the flow characteristics of the Flathead River despite accounting for only 40% of the annual flow of the Flathead River. The most obvious affect is the reduction in the percent of variance in common between the three streams and the Flathead River for the flow characteristics. The dammed river appeared be related to the variance early in the year, as a result of its earlier 25th quantile of flow. Once the spring melt begins in the undammed streams dictate the timing of the quantiles of flow for the Flathead River. The median flow discharge is associated with the undammed streams in the Flathead River.

Magilligan and Nislow (2005) and Graf (2006) point out that due to release schedules tailored to each dam research on a single dam cannot reach any general conclusions about dam operations. While it is difficult to make portable conclusions from a study based on one dam, this research may add to a larger body of evidence for downstream effects on dams. Therefore, this study may contribute to a large understanding of dam operation effects on streamflow in combination with other past and future research.

References

- Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438(7066), 303-309.
- Boxall, B. (2007). Governed puts global spin on state's need for dams: The administration says planet warming will melt snowpacks, so more storage is needed. L.A. Times, 12 January, B1.
- Bureau of Reclamation. (2002). *Voluntary environmental assessment interim operation of the VARQ flood control plan at hungry horse dam, MT* No. FONSI 02-02)Bureau of Reclamation Pacific Northwest Region.
- Cayan, D. R., Kammerdiener, S. A., Dettinger, M. D., Caprio, J. M., & Peterson, D. H. (2001). Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society*, 82(3), 399-415.
- Graf, W. L. (2006). Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology*, 79(3-4), 336-360.
- Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D. W., & Medina-Elizade, M. (2006). Global temperature change. *Proceedings of the National Academy of Sciences of the United States of America*, 103(39), 14288-14293.
- Lajoie, F., Assani, A. A., Roy, A. G., & Mesfioui, M. (2007). Impacts of dams on monthly flow characteristics. the influence of watershed size and seasons. *Journal of Hydrology*, 334(3), 423-439.
- Magilligan, F. J., & Nislow, K. H. (2005). Changes in hydrologic regime by dams. *Geomorphology*, 71(1-2), 61-78.

- McCabe, G. J., & Dettinger, M. D. (2002). Primary modes and predictability of year-to-year snowpack variations in the western United States from teleconnections with Pacific Ocean climate. *Journal of Hydrometeorology*, 3(1), 13.
- Moore, J. N., Harper, J. T., & Greenwood, M. C. (2007). Significance of trends toward earlier snowmelt runoff, Columbia and Missouri basin headwaters, western United States. *Geophysical Research Letters*, 34(16), L16402.
- Mote, P. W. (2003). Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophysical Research Letters*, 30(12), 1601.
- Mote, P. W. (2006). Climate-driven variability and trends in mountain snowpack in western North America. *Journal of Climate*, 19(23), 6209-6220.
- Olden, J. D., & Poff, N. L. (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications*, 19(2), 101-121.
- Payne, J. T., Wood, A. W., Hamlet, A. F., Palmer, R. N., & Lettenmaier, D. P. (2004). Mitigating the effects of climate change on the water resources of the Columbia River basin. *Climatic Change*, 62(1), 233-256.
- Peterson, D. H., Smith, R. E., Dettinger, M. D., Cayan, D. R., & Riddle, L. (2000). An organized signal in snowmelt runoff over the western United States. *Journal of the American Water Resources Association*, 36(2), 421-432.
- Singer, M. B. (2007). The influence of major dams on hydrology through the drainage network of the Sacramento River basin, California. *River Research and Applications*, 23(1), 55-72.
- Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2005). Changes toward earlier streamflow timing across western North America. *Journal of Climate*, 18(8), 1136-1155.

Tiku, M. L., Tan, W. Y., & Balakrishnan, N. (1986). *Robust inference*. New York: M. Dekker.

Wilcox, R. R. (2001). *Fundamentals of modern statistical methods: Substantially improving power and accuracy*. New York, New York: Springer.