# CLIMATIC AND PHYSIOGRAPHIC DRIVERS OF PEAK FLOWS IN WATERSHEDS IN THE NORTH SLOPE OF ALASKA

By
Alexa Marion Hassebroek Hinzman, B.S

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of

Master of Science
in
Civil Engineering

University of Alaska Fairbanks
August 2017

APPROVED:
Svetlana Stuefer, Committee Chair
Christopher Arp, Committee Member
David Barnes, Committee Member
Leroy Hulsey, Chair
*Department of Civil and Environmental Engineering*
Douglas J. Goering, Dean
*College of Engineering and Mines*
Michael Castellini, Dean
*Graduate School*

# Abstract

The failure to accurately predict peak discharge can cause large errors in risk analysis that may lead to damage to structures and in some cases, death. Creating linear regression (LR) equations that accurately predict peak discharges without historic data provides a method to estimate flood peaks in ungauged watersheds on the North Slope of Alaska.

This thesis looks at the independent variables that drive, or are significant in predicting snowmelt peak discharge in the North Slope watersheds. The LR equations created use independent variables from meteorological data and physiographic data collected from four watersheds, Putuligayuk River, Upper Kuparuk River, Imnavait Creek and Roche Moutonnée Creek. Meteorological data include snow water equivalent (SWE), total precipitation, rainfall, storage, length of melt. Physiographic data summarize watershed area (2.2 $km^2$ to 471 $km^2$) and slope (0.15:100 to 2.7:100).

This thesis compared various Flood Frequency Analysis techniques, starting with Bulletin 17B, multiple USGS regional methods and finally created LR equations for each watershed as well as all four watersheds combined. Five LR equations were created, three of the LR equations found SWE to be a significant predictor of peak flows. The first equation to estimate peak flows for all watersheds used only area and had a high $R^2$ value of 0.72. The second equation for all watersheds included area and a meteorological independent variable, SWE. While the evidence presented here is quite promising that meteorological and physiographic data can be useful in estimating peak flows in ungauged arctic watersheds, the limitations of using only four watersheds to determine the equations call for further testing and verification. More validation studies will be needed to demonstrate that viable equations may be applied to all watersheds on the North Slope of Alaska.

# Table of Contents

Page

**Title Page** ........ i

**Abstract** ........ iii

**Table of Contents** ........ v

**List of Figures** ........ ix

**List of Tables** ........ xiii

**Acknowledgements** ........ xv

**Chapter 1 Introduction** ........ 1

1.1 The Importance of Estimating Peak Discharge ........ 1

1.2 Users of Information on Peak Flows ........ 1

1.3 Current Gaps in Peak Flows Knowledge ........ 2

1.4 Research Questions ........ 3

**Chapter 2 Background and Study Area** ........ 5

2.1 Common Features ........ 7

2.2 Imnavait Creek ........ 7

2.3 Upper Kuparuk River ........ 8

2.4 Putuligayuk River ........ 9

2.5 Roche Moutonnée River ........ 11

**Chapter 3 Data and Data Collection** ........ 13

3.1 Streamflow ........ 13

3.2 Precipitation ........ 16

3.3 Storage ........ 18

**Chapter 4 Methods ........ 21**

4.1 Flood Frequency Analysis for Gauged Watersheds ........ 21

4.2 Ungauged Watersheds ........ 23

4.3 Linear Regression Model Equations ........ 25

*4.3.1 Single variable linear regression comparison ........ 27*

*4.3.2 Multiple linear regression ........ 27*

*4.3.3 Landscape characteristics ........ 28*

**Chapter 5 Results ........ 29**

5.1 Hydrographs and Peak Flows ........ 29

5.2 Flood Frequency Analysis ........ 31

*5.2.1 Upper Kuparuk River ........ 31*

*5.2.2 Putuligayuk River ........ 33*

*5.2.3 Imnavait Creek ........ 36*

*5.2.4 Roche Moutonnée Creek ........ 38*

*5.2.5 Comparison of FFA methods between watersheds ........ 40*

5.3 Linear Regression Analysis ........ 41

*5.3.1 Simple linear regression analysis ........ 41*

5.3.1.1 Upper Kuparuk River ........ 41

5.3.1.2 Putuligayuk River ........ 44

5.3.1.3 Imnavait Creek ........ 46

5.3.1.4 All Watersheds ........ 48

5.3.1.5 SWE Frequency Analysis ........ 50

*5.3.2 Simple or multiple linear regression equations ........ 52*

5.3.2.1 Upper Kuparuk River ........ 52

5.3.2.2 Putuligayuk River ........ 52

5.3.2.3 Imnavait Creek ........ 53

5.3.2.4 All Watersheds ........ 53

*5.3.3 Multiple linear regression ........ 54*

**Chapter 6 Discussion ........ 55**

**Chapter 7 Conclusions ........ 63**

**Literature Cited ........ 65**

**Appendix ........ 68**

## List of Figures

Page

Figure 1 Map of all study stations including outlines of the study watersheds, locations of snow survey sites and gauging locations. (Stuefer et al. 2016). ........ 6

Figure 2 Weir at Imnavait Creek, picture taken facing upstream (south). ........ 8

Figure 3 Upper Kuparuk River gauge site in May, facing upstream (south). ........ 9

Figure 4 Putuligayuk River around peak flow in May. ........ 10

Figure 5 The Putuligayuk River gauge site showcasing June flow. ........ 10

Figure 6 Roche Moutonnée Creek gauge site in July. The stilling well is USGS property. TEON staff gauge is to the right. ........ 11

Figure 7 Manually gauging Roche Moutonnée Creek with a Price AA Current Meter in May... 15

Figure 8 Comparison of observed 2015 hydrographs for the Putuligayuk River, Imnavait Creek, Roche Montonnée Creek and the Upper Kuparuk River. ........ 30

Figure 9 Comparison of observed normalized 2015 hydrographs for the Putuligayuk River, Imnavait Creek, Roche Montonnée Creek and the Upper Kuparuk River accounting for watershed area difference. ........ 31

Figure 10 Bulletin 17B FFA plot for Upper Kuparuk River. ........ 32

Figure 11 Bulletin 17B FFA plot for Putuligayuk River. ........ 34

Figure 12 Bulletin 17B FFA plot for Imnavait Creek ........................................................... 36

Figure 13 Bulletin 17B FFA plot for Roche Moutonnée Creek ................................................ 38

Figure 14 Comparison of Upper Kuparuk Watershed independent variables. Peak discharge is $Q_P$ ($m^3/s$). Julian day is the day of peak flow. Normalized peak discharge is $q_P$ (m/s). SWE is in centimeters. Rainfall, $P_R$ is centimeters. The numbers in the upper right of the matrix are correlation coefficients (r). The '*' in the corner shows independent variables that do not contain a complete dataset. ........................................................................................... 43

Figure 15 Comparison of independent variables of the Putuligayuk River Watershed. Year is year of peak discharge. Peak discharge is $Q_P$ ($m^3/s$). Normalized peak discharge is $q_P$, ($m^3/(s*km^2)$). Storage, S, is in millimeters. Precipitation, P, is in centimeters, Rainfall, $P_R$, is in centimeters. SWE is in centimeters. Length of melt, LoM, is in days. Rate of ablation, RoA, is SWE over day. The numbers in the upper right of the matrix are correlation coefficients (r). The '*' in the corner shows independent variables that do not contain a complete dataset. ........................................................................................... 45

Figure 16 Comparison of Imnavait Watershed independent variables. Year is year of peak discharge. Peak discharge is $Q_P$, ($m^3/s$), normalized peak discharge, $q_P$, ($m^3/(s*km^2)$), SWE is in centimeters and storage in is millimeters. Precipitation (P) is in centimeter. Rainfall ($P_r$)is in centimeters. Length of Melt (LoM) is the time in days it takes for SWE to become 0. Rate of Ablation (RoA) the rate of how quickly the SWE melted every day (cm/day). The numbers in the upper right of the matrix are correlation coefficients (r). The '*' in the corner shows independent variables that do not contain a complete dataset. ................................. 47

Figure 17 Comparison of independent variables of all study watersheds. Year is year of peak flow. Peak discharge is $Q_p$ ($m^3/s$), normalized peak discharge is $q_p$ ($m^3/(s*km^2)$), SWE is in centimeters, A is area ($km^2$) Storage is in millimeters, slope is km/km. The numbers in the upper right of the matrix are correlation coefficients (r). The '*' in the corner shows independent variables that do not extend the full dataset. .................................................... 49

Figure 18 Imnavait Creek Log-Pearson Type III SWE Frequency Analysis with equation. ....... 50

Figure 19 SWE Frequency Analysis for end-of-winter watershed-averaged SWE using log-normal distribution for 3 watersheds, Imnavait Creek, Upper Kuparuk River and Putuligayuk River. ........................................................................................................ 51

Figure 20 All Watersheds I linear regression equation line with the average historic peak discharge points and 95% confidence intervals from each watershed. ................................ 56

Figure 21 All watersheds II multiple linear regression equation and average historic peak flows and individual SWE frequency analysis points for 10-year and 100-year SWE. ................. 57

Figure 22 Upper Kuparuk River linear regression equation with historic peak discharge points compared with Equation 4 and with 95% confidence intervals in yellow, the verifying 2015 data point is green. ........................................................................................................ 59

Figure 23 Putuligayuk River linear regression equation with historic peak discharge points compared with Equation 9. ........................................................................................... 60

Figure 24 Imnavait Creek linear regression equation with historic peak discharge points compared with Equation 6 and 95% confidence intervals. ................................................. 61

Figure 25 Stage-Discharge Relation for Imnavait Creek Weir 2004-2008 and 2012-2015 (Kane and Hinzman 2009; Arp and Stuefer 2016). ........ 68

Figure 26 Upper Kuparuk River 1994-2002 Rating Curves Adjusted High Flow and Upper Kuparuk River 2005 to 2016 New Rating Curve To convert Tylers 2014 BM to old staff gauge add 0.73 ft. Stage-Discharge Relation for Upper Kuparuk Rive. (Kane and Hinzman 2009; Arp and Stuefer 2016) ........ 69

Figure 27 Stage-Discharge Relation for Putuligayuk River at Spine Road High Flow 1974 - 2015 (Kane and Hinzman 2009; Arp and Stuefer 2016). ........ 70

Figure 28 Stage-Discharge Relation for Roche Moutonnée Creek (U.S. Geological Survey 2016) The points are from TEON's new Roche Moutonnée gauging station. ........ 71

# List of Tables

Page

Table 1 Historic rainfall and SWE periods of record for all study sites. Current number of meteorological stations and snow survey sites is stated in parenthesis. ............................... 17

Table 2 2016 USGS flood frequency equations (Curran et al. 2016). A is watershed area in square miles. P is the basin average mean annual precipitation in inches from the PRISM climate dataset. ............................................................................................................ 24

Table 3 2003 USGS flood frequency equations (Curran, et al. 2003). A is watershed area in square miles. ................................................................................................................. 25

Table 4 Flood Frequency Analysis results for Upper Kuparuk River at Alyeska pipeline crossing. ............................................................................................................................ 33

Table 5 Flood Frequency Analysis results for Putuligayuk River near Spine Road. .................. 35

Table 6 Flood Frequency Analysis results using Bulletin 17B, the 2003 and 2016 USGS equations for Imnavait Creek. ....................................................................................... 37

Table 7 Flood Frequency Analysis results for Roche Moutonnée Creek. ................................... 39

Table 8 2-yr flood comparing the peak discharge estimates of different FFA methods.............. 40

Table 9 10-yr flood comparing the peak discharge estimates of different FFA methods............ 40

Table 10 100-yr flood comparing the peak discharge estimates of different FFA methods......... 41

Table 11 Final equations for peak discharge flows. .................................................................. 58

Table 12 Summary of hydrological and meteorological data for the Putuligayuk River Watershed. ........ 69

Table 13 Summary of hydrological and meteorological data for the Upper Kuparuk River Watershed. ........ 70

Table 14 Summary of hydrological and meteorological data for the Imnavait Creek Watershed. ........ 71

Table 15 Summary of hydrological and meteorological data for Roche Moutonnée Creek Watershed. ........ 73

Table 16 Summary of physiographic, hydrological and meteorological data for all watersheds. 74

# Acknowledgements

My greatest thanks to all the agencies that funded data collection, from the first year Imnavait Met was built to present day and multiple watersheds. Data collection is being done by Water and Environmental Research Center (WERC), University of Alaska Fairbanks and funded by many agencies including the Department of Energy, Office of Health and Environmental Research from 1984 to 1993, the National Science Foundation, Office of Polar Programs, from 1993 to 2010, Alaska Department of Transportation and Public Facilities (ADOT&PF) from 2008 to 2013 and the Arctic Landscape Conservation Cooperative (LCC) from 2013 to present. Since 2015, Terrestrial Environmental Observation Network (TEON) has accepted responsibility for monitoring the Kuparuk and adjacent watersheds and has continued with data collection. The Arctic LCC is funding TEON, which in turn is supporting my research.

I would like to thank all my committee members who read over multiple drafts even before I gave them my final first draft. Dr. David Barnes for his cut and dry approach to thesis writing and to Dr. Chris Arp for his statistic knowledge and ideas. I especially want to thank my main advisor Dr. Svetlana Stuefer, who is an amazing advisor and teacher, and who spent hours reading and correcting my thesis. I could not have picked a better advisor. I also thank my statistic professor Scott Goddard, who met with me several times and answered every question I had. I would also like to thank my mom, who allowed my 11 pm phone calls and constant patience when I needed to talk about my progress, my father, whose knowledge of the study sites is invaluable, my boyfriend who supported me through all my all-nighters, and did everything that I couldn't, and my sister for her gallows humor while she is going through her own thesis. I also want to thank my officemates, Carrie, Zhili, Beaux and friends, Madison, Sara, Sally and Joe who lent their ears for any problem, complaint or quandary that would come to mind.

# Chapter 1 Introduction

## 1.1 The Importance of Estimating Peak Discharge

Water affects all landscapes, rural or urban. While management for rural and urban systems are vastly different, it is important to account for the mechanisms of water movement through a watershed to properly manage risk and design safety standards for a watershed's high flows. To manage risks associated with flooding, engineers often rely on frequency analysis of peak flow data. The hydrologic and hydraulic design criteria are specified in the building standards and codes. For example, every major highway bridge in Alaska must be designed based on the 50-yr hydraulic design or 100-yr scour design, whichever is largest (Knapp 2016). Structures are built to withstand peak flows of a certain flood frequency, a design flow. The choice of the design flow is determined by how much risk is acceptable and the cost of construction.

Peak flow (or peak discharge) is defined as the greatest point of a hydrograph, or the highest discharge during a precipitation or snowmelt event (Wurbs and James 2002). The peak flows can be generated by a heavy rain storm or snowmelt. Research has shown that large watersheds in the Arctic have peak flows related to snowmelt (McNamara et al. 1998). Smaller Arctic watersheds can have peak flows related to rainfall because localized events such as a rain event will affect a smaller area more than a large area (Kane et al. 2003).

## 1.2 Users of Information on Peak Flows

Streamflow data are critical for assessing hazard management, environmental research and waste water management. Alaska Department of Transportation and Public Facilities (ADOT&PF) and United States Army Corps of Engineers (USACE) use available historic discharge data when designing bridges, culverts, floodplains or reservoirs.

One of the largest floods in the history of Fairbanks occurred in 1967. The flood caused $85M dollars in damage, adjusted for inflation that is $627M dollars' worth of damage today. The Chena River Lakes Flood Control Project was created by the USACE to reduce the chance of flooding in Fairbanks and North Pole, and historic peak flows were used for sizing the hydraulic structures for this project (USACE 2015).

The 2015 flooding of Dalton Highway near Deadhorse caused sections of the road to be washed away (Bailey 2016). The damaged is estimated to cost the State of Alaska $17M to emergency repair and $31M for reconstruction (Bailey 2016).The damaged sections of Dalton highway were recently reconstructed by ADOT&PF using historic data on peak flows and flood elevation (Bailey 2016). The Dalton highway was closed for 28 days due to aufeis and break-up flooding (Bailey 2016).

### 1.3 Current Gaps in Peak Flows Knowledge

Incomplete and/or short historic peak flow datasets with less than 10 years of data collection is the biggest hurdle when estimating peak flows in Alaska. Most of the long-term streamflow data are collected by the US Geologic Survey (USGS). USGS collects and manages water data for other federal or state agencies, and private, business and industry uses.

Areas that are inaccessible or less populated tend to lack the historic streamflow data necessary for determining peak flows. This is common for the North Slope of Alaska since there are large swaths of isolated areas. At the same time, the North Slope of Alaska has potential for growth and human development, associated with exploration of natural resources (Kane et al. 2014). This would require baseline hydrologic and weather data for design and construction (Kane et al. 2012). This thesis focuses on Arctic region of Alaska (North Slope of Alaska), which has a sparse gauging network.

Arctic Rivers, including the North Slope of Alaska watersheds, are also sensitive to climate warming (McNamara et al. 1998). Peak flows in the Arctic will become more important as warming climate influences the amount of freshwater available (McNamara et al. 1999).

## 1.4 Research Questions

My first research question is what climatic drivers control the magnitude of peak flows in North Slope of Alaska watersheds? My hypothesis is that the spatial distribution and quantity of end of winter snow water equivalent, and rain will influence the peak flows in the Arctic watersheds.

My second research question involves finding what geographic factors control magnitude of peak flows in the North Slopes watersheds. My hypothesis for this question is that the size of watershed, topography, storage zones and gradient of the watershed are the greatest drivers in peak flows.

To answer these research questions, four Arctic watersheds on the North Slope, each with unique characteristics will be used.

# Chapter 2 Background and Study Area

The study area, located north of the Brooks Range in Alaska covering domain from 68°N to 70°N. It includes four watersheds: Putuligayuk River watershed on the coastal plane, Imnavait Creek watershed in the foothills of the Brooks Range in Alaska, the Upper Kuparuk watershed in the foothills of the Brooks Range, and Roche Moutonnée watershed in the northern Brooks Range. Figure 1 on the following page shows the location of all meteorological and river gauging sites.

The current hydrological and weather research observational network in Kuparuk River watershed started with measurements in the Imnavait Creek in 1985. Gauging and meteorological data collection in the Upper Kuparuk River started in 1993. Putuligayuk River started hydrologic data collection in 1999 and a new meteorological site was added in 2015. Roche Moutonnée Creek hydrological and meteorological stations were installed in 2015.

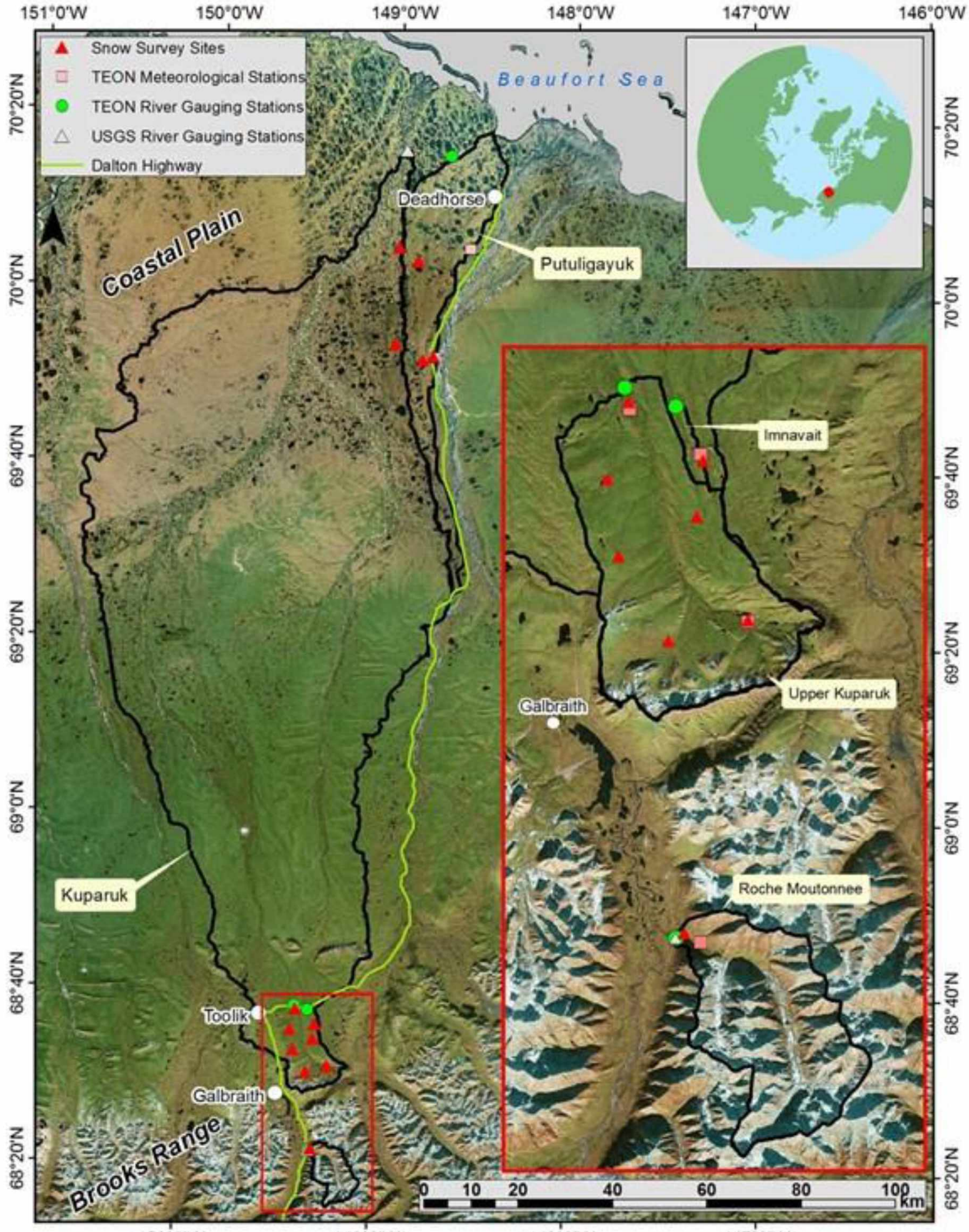

*Figure 1 Map of all study stations including outlines of the study watersheds, locations of snow survey sites and gauging locations.* (Stuefer et al. 2016).

## 2.1 Common Features

All study rivers share several common features. Continuous permafrost is present in all four watersheds. Permafrost is frozen ground which remains frozen for at least two consecutive years. The existence of permafrost is dependent on the temperature of the soil, a temperature that has been becoming increasingly warmer due to climate change (Romanovsky et al. 2010).

High runoff ratios (runoff divided by precipitation) are typical for watersheds with permafrost presence (McNamara et al. 1998). These watersheds have low growing vegetation and short growing periods. Climate is characterized by a prolonged season of below freezing air temperatures and long periods, up to 8 months of snow cover presence. Rivers and lakes have seasonal ice cover. Aufeis can be found in Upper Kuparuk if certain conditions exist, such as groundwater upwelling or human development changing the groundwater flow. Upper Kuparuk has had aufeis development for perhaps thousands of years (Yoshikawa et al. 2007).

All study sites are in unpopulated areas except for Putuligayuk River which has a small presence of oilfield workers. There is no winter channel flow for Imnavait Creek, Upper Kuparuk River and the Putuligayuk River, meaning during the winter the stream channel is frozen solid and therefore runoff only happens in once break up occurs in spring, summer and ends in fall.

## 2.2 Imnavait Creek

Imnavait Creek is a small watershed with an area of 2.2 km$^2$. It is located 1 km east of the Upper Kuparuk River gauging site and is a tributary of the Kuparuk River. It is a north-northwest trending glacial valley in rolling hills (Hamilton 2003). Imnavait Creek has been monitored since 1985. Imnavait Creek is underlain with continuous permafrost. The average elevation of the basin is around 904 meters. The channel is 1 meter wide but shallow, with overbank flow occurring during peak flows. Imnavait Creek's stream gauge site has a weir to aid in discharge measurements. Using a weir helps during peak flows by forcing the creek to go through one section of channel without overbank flow to insure an accurate discharge measurement. The creek is commonly described as a chain of small ponds called beads, where the water eroded massive chunks of ground ice (McNamara et al. 1998). During snowmelt, the snow in the channel of Imnavait Creek must be removed up and downstream of the weir or else the snow will hinder flow and cause backwater and inaccurate gauging measurements.

*Figure 2 Weir at Imnavait Creek, picture taken facing upstream (south).*

## 2.3 Upper Kuparuk River

Upper Kuparuk River watershed has an area of 142 km$^2$. It is in the rolling hills with headwaters in the Brooks Range. The Upper Kuparuk watershed is underlain with continuous permafrost (Hamilton 2003). Upper Kuparuk has an average elevation of 967 meters. The meteorological station is located on a north facing slope within 100 meters of Upper Kuparuk.

The gauging station was established in 1994 by Water and Environmental Research Center (WERC). The occurrence of larger rocks in the streambed can cause pockets of backwater within the channel. There are small shrubs, under one meter in height, along the river bank (McNamara et al. 1998). The Upper Kuparuk watershed is boarded by the Imnavait Creek watershed.

*Figure 3 Upper Kuparuk River gauge site in May, facing upstream (south).*

## 2.4 Putuligayuk River

The Putuligayuk River watershed has an area of 471 km$^2$. It is located on the coastal plain of the North Slope of Alaska with an average elevation of 10 m above sea level. It has the lowest gradient of the study watersheds, with permafrost thickness estimated at 600 meters (Bowling et al. 2003). At peak flow the river is too deep and too fast to be waded safely during high flows in May and June. The entire watershed is underlain with continuous permafrost.

*Figure 4 Putuligayuk River around peak flow in May.*

The Putuligayuk River streambed is made up of loose gravel. Any sands or fine particles present in the riverbed are swept downstream every spring. The width of the channel flow is 25 meters during the snowmelt season (Figure 4) (Bowling et al. 2003). During the rest of the summer, the width of the channel flow is reduced to only a few meters wide (Figure 5). Figure 4 and Figure 5 shows how much the Putuligayuk River diminishes over a single month. Most of the stream flow during the summer is very low flow, discharge less than 1 $m^3/s$ is usual.

Figure 5 The Putuligayuk River gauge site showcasing June flow.

*Figure 6 Roche Moutonnée Creek gauge site in July. The stilling well is USGS property. TEON staff gauge is to the right.*

### 2.5 Roche Moutonnée River

Roche Mountonée River has a watershed area of 84 km$^2$. It is a high gradient watershed with an average elevation of 927 meters, located in the northern Brooks Range south of Toolik Lake. Roche Moutonnée's channel has steep banks and is filled with rocks which makes wading across dangerous, therefore discharge measurements are taken farther downstream from the stilling well, after the bridge in a section with less rocks.

Figure 6 shows the USGS stilling well and staff gauge. The river has been monitored by USGS since 1973.

# Chapter 3 Data and Data Collection

Hydrometeorological data collected by the different agencies previously mentioned includes United States Geographical Survey (USGS) and WERC. Collected hydrometeorological data includes hydrological (streamflow, stream temperature, stage) and meteorological data (air temperature, wind speed and direction, precipitation, relative humidity and atmospheric pressure). Hydrologic data are collected directly from the river channel at the gauging stations and meteorological data are collected at weather stations. Gauging stations are placed near the river channel; weather stations are distributed across the watershed. Data collected by instruments in stations are uploaded in near real time by telemetry. Some data are collected in person on field trips, which happen 3-4 times a year, while some data are collected automatically.

## 3.1 Streamflow

While manual discharge or stage measurements are done when the researcher is in the field, automatic stage measurements are recorded during the ice-free period, in specific time intervals and recorded in a data logger. The time intervals vary for each type of measurement. Streamflow (or discharge) is calculated from manual velocity measurements taken at a defined cross-section for each river. It is possible to calculate rating curves for the Putuligayuk River, Imnavait Creek, Upper Kuparuk and Roche Moutonnée Creek from the historic data. The Roche Moutonnée Creek rating curve was created by the USGS (Appendix, Figure 27). Stream stage data is collected hourly as well as water temperature. At the same time, the meteorological sites at each station collect air temperature, precipitation, wind speed, and air humidity.

Accurate automatic measurements of river stage are challenging when the riverbed is filled with ice, as the instruments becomes frozen in the ice and the cross-sectional area of the channel changes day to day as the ice melts. Therefore, researchers must be in the field during snowmelt and break up to collect peak discharge data. In-field measurements by TEON researchers use many instruments; for all four watersheds, an Acoustic Doppler Current Profiler (ADCP), a Sontek Flowtracker, the Hack Electromagnetic Current Meter, a Price AA Current Meter, or a Price Pygmy Current Meter are used depending on conditions. Each instrument is used for different channels per their flow characteristics. The ADCP is used in rivers when the flows are too high for a researcher to safely wade, such as the Putuligayuk River and Upper Kuparuk River during snowmelt. The Price Pygmy Current Meter is used in streams or creeks with low velocity flows, such as Imnavait Creek.

Arctic researchers have a unique challenge when measuring river discharge during snowmelt. During snowmelt, the channel is filled with ice which can cause jams or overbank flow. With ice in the channel, no rating curve is accurate, therefore, to record snowmelt peak flows, in-field measurements are required. If a researcher is unable to be in-field during melt, that year's peak flow data will be lost. Figure 7 shows Roche Moutonnée Creek being gauged while ice is still in the channel and along the bank. In stream measurements are often collected at times when no ice persists in the channel to verify or improve stream rating curves.

*Figure 7 Manually gauging Roche Moutonnée Creek with a Price AA Current Meter in May.*

There are also automatic methods to estimate discharge while not in field. Most discharge estimates come from stage measurements and rating curves. Rating curves developed from manual discharge measurements and stream stage readings taken simultaneously.

The rating curve (also known as a stage discharge relationship) for Imnavait Creek may be complicated by backwater and low flow (Appendix, Figure 24). Points on rating curves indicate concurrent stage and discharges measurements taken manually used to verify the relationship for different years. In 2012, it was found the weir had shifted and new stage-discharge relations had to be created. In Figure 24, manual measurements from 2004-2008 and 2012 and 2015 were used.

Once the rating curve is created and the stage and discharge relation established, only the stream stage reading is needed to estimate stream discharge. Streamflow with ice in the channels do not follow the rating curves and therefore to get an accurate discharge reading, discharge measurements must be done in-field. When in-field measurements are done, the stage, or depth of the flow is recorded. Rating curves are verified and updated every year. The stream stage is automatically recorded at the staff gauge every minute and then averaged over an hour using a INW AquiStar SDI-12 pressure transducer and CR1000X data logger. Imnavait Creek has two staff gauges to record stage data. One staff gauge is mid-stream and one staff gauge is on the side of the weir. The Upper Kuparuk staff gauge is attached to metal poles that have been driven into the stream. The Roche Moutonnée Creek staff gauge is attached to a metal pole placed next to the USGS stilling well.

### 3.2 Precipitation

Precipitation comes as liquid, solid or mixed. Liquid precipitation is rainfall, solid precipitation is snowfall, graupel, or sleet. Liquid precipitation at all meteorological stations is measured automatically by a tipping bucket gauge surrounded by an Alter wind shield. The Imnavait watershed has one rain gauge, at the meteorological station (Table 1). The Imnavait meteorological station rests east of the gauging site, on a hill. At peak operation, Upper Kuparuk had six different meteorological sites with rain gauges at each station. But since 2013, Upper Kuparuk operation has been reduced to two meteorological sites and two rain gauges (Table 1). Roche Mountonée has one rain gauge. As Roche Moutonnée Creek meteorological station was established by the TEON in 2015, there has only been two years of meteorological data. Putuligayuk River currently has two rain gauges at Putuligayuk meteorological station and Franklin Bluffs meteorological station. The Putuligayuk meteorological station was established in 2015. The Franklin Bluffs meteorological station is located near headwaters of Putuligayuk River. It was established in 1982.

There are two more weather stations in the Putuligayuk River Basin, Betty Pingo and West Dock. Betty Pingo started operation in 1994 and was removed in 2011, West Dock started operation in 1995 and was removed in 2008. Betty Pingo and Franklin Bluffs were used to represent meteorological data for the Putuligayuk River before the Putuligayuk meteorological site started operation, West Dock is too close to the coast to be considered an accurate representation of the watershed. However West Dock, Betty Pingo and Franklin Bluffs have been SWE survey sites (Bowling et al. 2003).

*Table 1 Historic rainfall and SWE periods of record for all study sites. Current number of meteorological stations and snow survey sites is stated in parenthesis.*

| | Rainfall | | Snow Water Equivalent | |
|---|---|---|---|---|
| | Period of records | Number of sites | Period of records | Number of sites |
| Upper Kuparuk River | 1994-Present | 6 (2) | 1996-Present | 21 (7) |
| Putuligayuk River | 1999-Present | 3 (2) | 1999-Present | 12 (5) |
| Imnavait Creek | 1986-Present | 1 | 1988-Present | 10 |
| Roche Moutonnée Creek | 2015-Present | 1 | 2016-Present | 1 |

Solid precipitation is measured manually as snow water equivalent (SWE) accumulated on the ground during cold season. SWE is the water content obtained from melting accumulated snow (Wurbs and James 2002). The equation for SWE is shown below.

$$SWE = \frac{h\rho_s}{\rho_w}$$

(1)

Where $h$ is the average depth of 50 snow depth measurements, $\rho_s$ is the average snow density from 5 snow cores and $\rho_w$ is the density of water (Stuefer, Kane, and Liston 2013). SWE measurements are collected in-field at the end of winter. The accuracy of the SWE estimates is 10% (Stuefer, et al. 2013). The error can come from driving the snow depth probe past the organic layer or a snow depth probe mistaking an ice layer for the organic layer (Stuefer et al. 2013). The number of meteorological stations and snow survey sites have changed over the years (Table 1). These changes in observational network are associated with the availability of research funding (Kane et al. 2014).

Upper Kuparuk River, Imnavait Creek and Putuligayuk River have had extensive snow surveys done for many years throughout the entire watershed. Roche Moutonnée Creek has more than 30 years of peak flow data from the USGS, however there is no meteorological data collection. Due to lack of meteorological data for Roche Moutonnée Creek, the study site will only be included for the second research question. Roche Moutonnée Creek can be used to compare landscape characteristics with the three other watersheds.

Snow ablation is the melting and evaporation of snow through heat transfer from short and long wave radiation and turbulent surface fluxes of convective and latent heat exchange. The rate of ablation (RoA) was monitored through field measurements at the Imnavait Creek watershed, Upper Kuparuk meteorological station and intermittently at the Franklin Bluffs meteorological station. The RoA is used to show how quickly ablation is occurring, indicative of temperature and radiation.

### 3.3 Storage

There are two types of water storage in a watershed: subsurface water storage and surface water storage. Subsurface water storage occurs primarily in the active layer soils set above the permafrost table. Surface water storage is primarily in the form of wetland, ponds, lakes and other depressions. Surface water storage can be measured un-intrusively, but subsurface groundwater needs much invasive data collection into the ground. While difficult, subsurface data collection is not impossible. Storage data is estimated with an equation, the water balance equation, shown below

$$(Rainfall + SWE) - Runoff - ET = \pm\Delta S \tag{2}$$

Where rainfall and snow water equivalent (SWE) are precipitation, runoff is channel discharge and ET is evapotranspiration, defined as the amount of water that leaves the watershed system in the form of evaporation. The residual of the calculation is the amount of water attributed to storage ($\Delta S$). A negative storage means dry ground and a positive storage means wet ground. This approach assumes that error terms in each water balance component cancel each other (Bowling et al. 2003).

# Chapter 4 Methods

Methods for peak flow analysis are presented in terms of data availability. The methods vary based on rivers that have historical peak flow measurements; and rivers that have no peak flow measurements. When watersheds do not have historic peak flow data, methods require physical or statistical models to estimate peak flows from other data, such as precipitation (Wurbs and James 2002).

## 4.1 Flood Frequency Analysis for Gauged Watersheds

Flood frequency analysis (FFA) is a method to determine design discharge based on historical peak flow observations. FFA performed under the assumption that peak flows are a random variable, and to be associated with measures of frequency like percentage of time, annual exceedance probability and risk (Wurbs and James 2002). FFA is essential to hydrologic design risk assessment and evaluation, failure to correctly conduct and interpret FFA might lead to property damage and risk life (Wurbs and James 2002). FFA requires at least 10 historic peak flows to be considered statistically accurate (Bulletin 17B).

The equation for risk (R) is

$$R = 1 - (1 - AEP)^N$$

(3)

Where AEP is annual exceedance probability (unitless), and N is number of years a flood event did not exceed AEP.

Risk is determined by annual exceedance probability (AEP) and design life of the structure. The AEP is the percent chance that a specified magnitude will be equaled or exceeded in any given year (Wurbs and James 2002). It is important to acknowledge that the occurrence of a rare flood in one year does not reduce the chances of another rare flood within the next few years. The recurrence interval (or return period) is the reciprocal of the AEP. For example, the recurrence interval of 100 years (100-year flood) corresponds to AEP 0.01 (1/100). The 100-year recurrence interval and corresponding AEP refers to a 1 % chance of a given flood occurring every year.

Procedure for FFA are standardized in Bulletin 17B, a guideline published in 1976 and then revised in 1982 (U.S. Interagency Advisory Committee on Water Data 1982). The Hydrology Committee of the former U.S. Water Resources Council developed guidelines for flood frequency analysis to be followed by all federal and state water agencies. The most recent update for the Bulletin 17C was opened for public feedback in 2015. Bulletin 17B requires a long historic data collection to be performed. The FFA estimates are computed with log-Pearson Type III distribution, (U.S. Interagency Advisory Committee on Water Data 1982), as shown in Tables 4-7. Confidence intervals show the measure of uncertainty of a selected exceedance probability, a larger sample size means a reduced confidence interval (U.S. Interagency Advisory Committee on Water Data 1982). The FFA estimate tables report computed flow and expected flow. Both the computed and the expected flow use the log Pearson type III method. The difference between the two is; the expected flow is adjusted to take into account the length of the record and any outliers in the data set.

US Army Corps of Engineers Hydrologic Engineering Center (HEC) developed a Statistical Software Package (HEC-SSP) to perform statistical analysis of hydrologic data including flood flow frequency analysis using Bulletin 17B (U.S. Interagency Advisory Committee on Water Data 1982) and Bulletin 17C (U.S. Interagency Advisory Committee on Water Data 2016). HEC-SSP was used to perform a flood frequency analysis for all four North Slope watersheds.

## 4.2 Ungauged Watersheds

Watershed models are one method that can be used to estimate design peak flows in ungauged watersheds. These models require different types of meteorological, hydrologic and/or conceptual data. For example, actual observed rainfall or synthetic storm data are used as an input to models. Watershed time of concentration and lag time are conceptual parameters used in different modeling techniques. Unit hydrographs are examples of another modeling method to convert rainfall to hydrograph. Computer models, such as HEC-HMS, EPA-Stormwater Management Model (SWMM) or Agricultural Research Service (ARS) are a common modeling technique that include suites of methods to transform precipitation input into the channel hydrograph.

Regional regression equations are another method for estimating peak flows, this method is recommended by the USGS report. The USGS equations are widely used to predict peak flow at different percent annual exceedance probabilities such as percent AEP50, percent AEP20 or percent AEP0.2 in ungauged and gauged sites across Alaska. Percent AEP is to be read as a fraction, for example percent AEP20 is 20%, or 1/5, which corresponds to a 5-year recurrence interval. The smaller the percent AEP, the larger the magnitude of the event (Wurbs and James 2002).

USGS has recently published a report updating statistical equations for watersheds in Alaska and Northern Canada. The 2016 paper entitled “Estimating Flood Magnitude and Frequency on streams in Alaska and Conterminous Basins in Canada, Based on Data through Water Year 2012” utilizes 18 variables to find the best equations for estimating annual exceedance probability discharge (Curran et al. 2016). The resulting equations use two variables; drainage area and basin average mean annual precipitation.

The previous (2003) USGS guidelines on estimating flood magnitude and frequency used a regional approach, resulting in a singular set of equations for estimating peak flow magnitude and frequency in each region. The last USGS edition used equations that would utilize 1 to 4 variables in each of the six regions of the state of Alaska and conterminous Canada (Curran et al. 2003). The 2016 USGS report is based on generalized least-squares regression, a method used to improve the equations by accounting for time-sampling error, a function of record length, and the cross-correlation of annual peak flows between stream gauges. Least-squares regression, also called ordinary least squares estimation, is a statistical method for estimating changes in a dependent variable with a linear relation to one or more independent variable. It is used to obtain estimates of parameters in a model to minimize the residual sum of squares (Weisberg 2014). The lower the residual sum of squares, the less deviation from the predicted value of data, the better the data fits with the linear regression line.

One of the variables (mean annual precipitation) used in the 2016 USGS regional equations comes from Parameter-elevation Regressions on Independent Slopes Model (PRISM), a spatial climate dataset for short and long term climate patterns (Curran et al. 2016).

*Table 2 2016 USGS flood frequency equations (Curran et al. 2016). A is watershed area in square miles. P is the basin average mean annual precipitation in inches from the PRISM climate dataset.*

| Annual Exceedance Probability (%) | 2016 USGS Regional Equations |
|---|---|
| 50 | $0.944A^{0.836}*P^{1.023}$ |
| 20 | $2.47A^{0.795}*P^{0.916}$ |
| 10 | $4.01\ A^{0.775}*P^{0.865}$ |
| 4 | $6.53\ A^{0.755}*P^{0.816}$ |
| 2 | $8.79\ A^{0.743}*P^{0.787}$ |
| 1 | $11.4\ A^{0.732}*P^{0.764}$ |
| 0.5 | $14.3\ A^{0.723}*P^{0.744}$ |
| 0.2 | $18.7\ A^{0.712}*P^{0.721}$ |

In the 2016 USGS report, the reason for having included all areas of Alaska and parts of Canada into one large study site was to increase the statistical strength of the regression equations (Curran et al. 2016). The 2003 USGS report used 7 gauging sites to create the region 7 equations (Curran et al. 2003), the region includes the North Slope of Alaska.

*Table 3 2003 USGS flood frequency equations* (Curran et al. 2003). *A is watershed area in square miles.*

| Annual Exceedance Probability (%) | 2003 USGS Region 7 Equations |
|---|---|
| 50 | $28.07* A^{0.8916}$ |
| 20 | $47.51*A^{0.8691}$ |
| 10 | $61.00*A^{0.8588}$ |
| 4 | $78.33*A^{0.8486}$ |
| 2 | $91.29*A^{0.8424}$ |
| 1 | $104.2*A^{0.8370}$ |
| 0.5 | $117.1*A^{0.8322}$ |
| 0.2 | $134.2*A^{0.8266}$ |

### 4.3 Linear Regression Model Equations

Having reviewed the existing means for statistically predicting peak flows (estimating AEP discharge), this part of the research is focused on linear regression analysis using the historic data to improve statistical equations that represent the North Slope of Alaska watersheds.

The linear regression approach is applied to model the relationship between a dependent variable ($y_i$) to one independent variable ($x_i$) looking at the relationship between x and y as linear. Multiple linear regression is when there are more than one independent variables. Linear regression modeling is used to summarize observed data as simply as possible (Weisberg 2014). The dependent variable in this analysis is peak discharge. In simple terms, independent variables are tested to find any significance to the peak discharge. The independent variables in this analysis are meteorological data, such as precipitation, snow water equivalent (SWE), storage and length of melt (LoM), or physiographic characteristics, such as watershed area and slope.

The coefficient of determination ($R^2$) is the proportion of variability in a data set that is accounted for by a statistical model, in simple linear regression this is the proportion of variability in response variable $y$ accounted for by the predictor variable $x$ (Weisberg 2014).

The equation is

$$R^2 = \frac{(SXY)^2}{SXX \times SYY} \tag{4}$$

where SXY is the sum of cross-products $(\Sigma(x_i - \bar{x})^2 * \Sigma(y_i - \bar{y})^2)$, SXX is the sum of squares for the $x$s: $(\Sigma(x_i - \bar{x})^2)$, SYY is the sum of squares for the $y$s: $(\Sigma(y_i - \bar{y})^2)$.

An adjusted $R^2$ can be created by using a correction of sum of squares used for easily comparing models in multiple regression. The correlation coefficient (r) is a number between -1 and +1 calculated to represent the linear dependence between two variables and showing the strength and direction of the dependence (Weisberg 2014).

The correlation coefficient, r, may be calculated:

$$r = \frac{SXY}{\sqrt{SXX \times SYY}} \tag{5}$$

SXY is the sum of cross-products $(\Sigma(x_i - \bar{x})^2 * \Sigma(y_i - \bar{y})^2)$, SXX is the sum of squares for the $x$s: $(\Sigma(x_i - \bar{x})^2)$, SYY is the sum of squares for the $y$s: $(\Sigma(y_i - \bar{y})^2)$ (Weisberg 2014). P-values show the level of marginal significance within a statistical hypothesis test representing the probability of the occurrence of a given event. If the p-value is significant, then the null hypothesis is rejected. The null hypothesis states there is no difference between the means and thus a significant difference doesn't exist (Weisberg 2014). Confidence intervals or confidence limits is the range of values representing a specified probability that the value of the parameters lies, the result are interval estimates (Weisberg 2014).

### 4.3.1 Single variable linear regression comparison

Simple linear regression is the first method. A simple linear model equation with an intercept is written as

$$y_i = \beta_0 + \beta x_i + e_i. \tag{6}$$

$y_i$ is the dependent variable peak flow; $\beta_0$ is the intercept; $x_i$ is the independent variable included in the linear regression and $\beta$ is the coefficient to that independent variable; $e_i$ is error.

### 4.3.2 Multiple linear regression

Once simple linear regression has shown which independent variables might impact peak flows, the variables can be added together to create linear regression equations that together potentially explain a larger portion of variation (greater adjusted $R^2$ values) and provide a fuller representation of the correlates or drivers of peak flow magnitude. The approach is used to find which independent variables in which combinations creates the equation with the highest correlation for each watershed.

A multiple linear model equation looks as such

$$y_i = \beta_0 + x_{i1}\beta_1 + \cdots + x_{ip}\beta_p + e_i \tag{7}$$

where $y_i$ is the dependent variable, in this case, peak flows; $\beta_0$ is the intercept; $x_{ip}$ is any independent variable included in the linear regression and $\beta_p$ is the coefficient to that independent variable ($x_{ip}$); $e_i$ is error.

The amount of data used in my model are important consideration. If an independent variable has less than 10 data points, statistically, the variables will not lend itself to a credible linear regression equation. Variables with less than 10 data points were not included in this study. I took this number from the USGS report as they used this number as a guideline for including or excluding watersheds.

### 4.3.3 Landscape characteristics

As landscape characteristics typically do not vary within a single watershed over short time scales (i.e. period of gauging records), they are considered constant. However, comparing multiple watersheds together allow for landscape characteristics to become independent variables and then can be used in a multiple linear regression. This linear regression method begins with combining all watersheds and then adding variables that are no longer constant, such as slope or area or percent of watersheds covered in water.

Some watersheds do not have the independent variables that have been measured and are available to the public. For example, Roche Moutonnée Creek only has peak flows, slope and area. Putuligayuk River has peak flows, slope, area, storage and rainfall. If the watershed does not have data for a specific variable, the watershed could not be included in the linear regression.

# Chapter 5 Results

## 5.1 Hydrographs and Peak Flows

Hydrographs shown on Figure 7 illustrate the difference in magnitude of peak flows for 4 watersheds in 2015. I picked 2015 because of the large flood that shut down the Dalton Highway, and I also collected, processed and quality checked the streamflow data for this year. The Putuligayuk River has the greatest peak flow, around 110 $m^3/s$, while Imnavait Creek has the lowest peak flow, around 1 $m^3/s$. Peak flows in all four rivers in 2015 were caused by snowmelt.

Specific discharge ($q_p$) is discharge divided by area ($m^3/s/km^2$). Dividing the peak flow by area is a method to normalize for the effect of the size of the watershed. Comparing the hydrograph on Figure 7 and Figure 8, it becomes apparent that the peak flows normalized by area are dramatically different. Imnavait Creek, while the smallest peak flow, has the highest normalized discharge. Putuligayuk River has the third smallest normalized discharge, but the greatest peak flow.

While the specific discharge normalizes the influence of area, there are still other independent variables that affect the magnitude of peak flow.

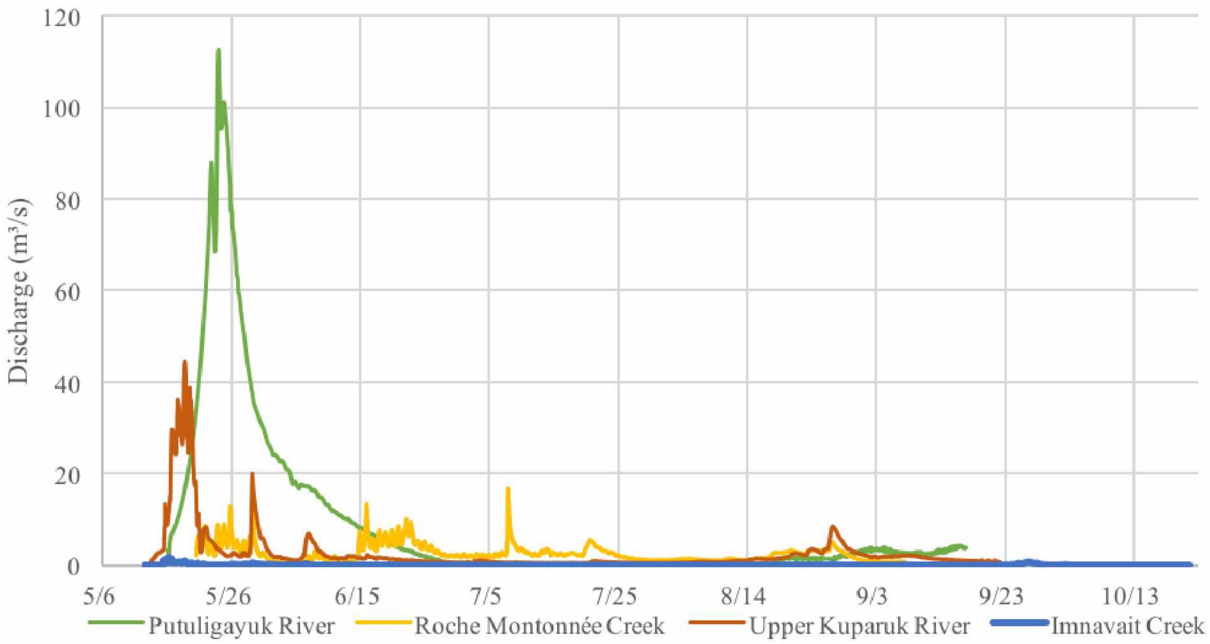

*Figure 8 Comparison of observed 2015 hydrographs for the Putuligayuk River, Imnavait Creek, Roche Montonnée Creek and the Upper Kuparuk River.*

The peak flows without the influence of area is shown in Figure 8, Imnavait Creek has become the greatest specific discharge peak (about 0.72 $m^3/(s*km^2)$), followed by Upper Kuparuk River (around 0.31 $m^3/(s*km^2)$), the Putuligayuk River (about 0.23 $m^3/(s*km^2)$) and finally Roche Moutonnée Creek with a peak of about 0.17 $m^3/(s*km^2)$. This suggest that Imnavait Creek has a high rate of runoff per $km^2$ and the Putuligayuk River has a lower rate of runoff per $km^2$ compared to Imnavait Creek and the Upper Kuparuk River.

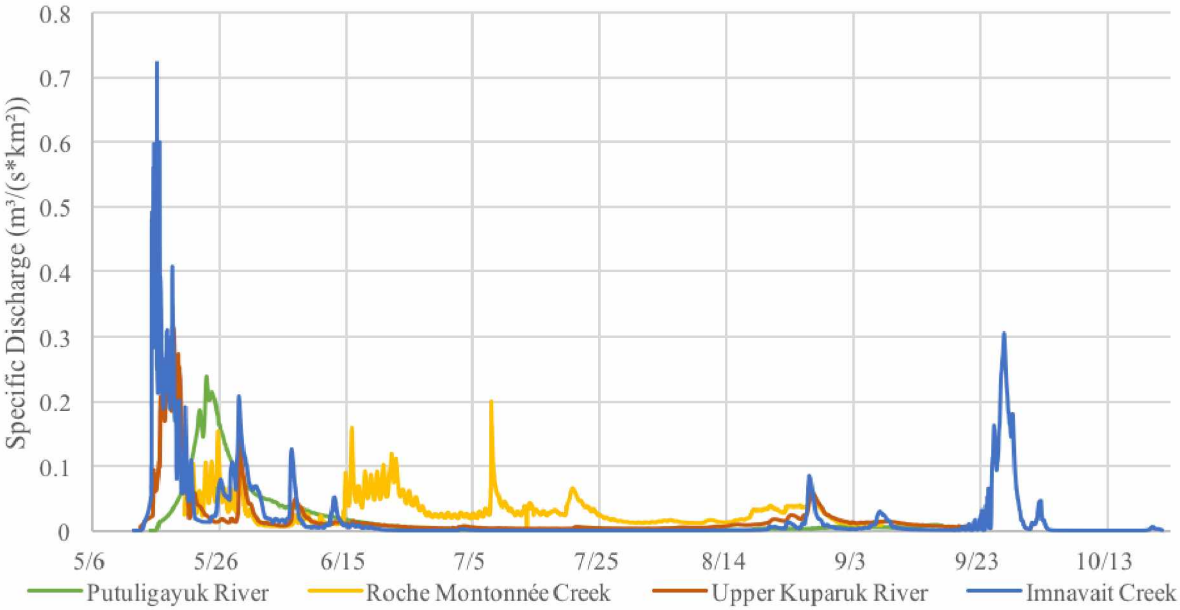

*Figure 9 Comparison of observed normalized 2015 hydrographs for the Putuligayuk River, Imnavait Creek, Roche Montonnée Creek and the Upper Kuparuk River accounting for watershed area difference.*

## 5.2 Flood Frequency Analysis

### 5.2.1 Upper Kuparuk River

The graphical representation of the Bulletin 17B FFA for the Upper Kuparuk River with HEC-SSP (Figure 9) has observed snowmelt peak flows in blue points (n = 23), with the confidence intervals in the green dotted line. There is one observed event considered to be a low outlier, during the year of 2008.

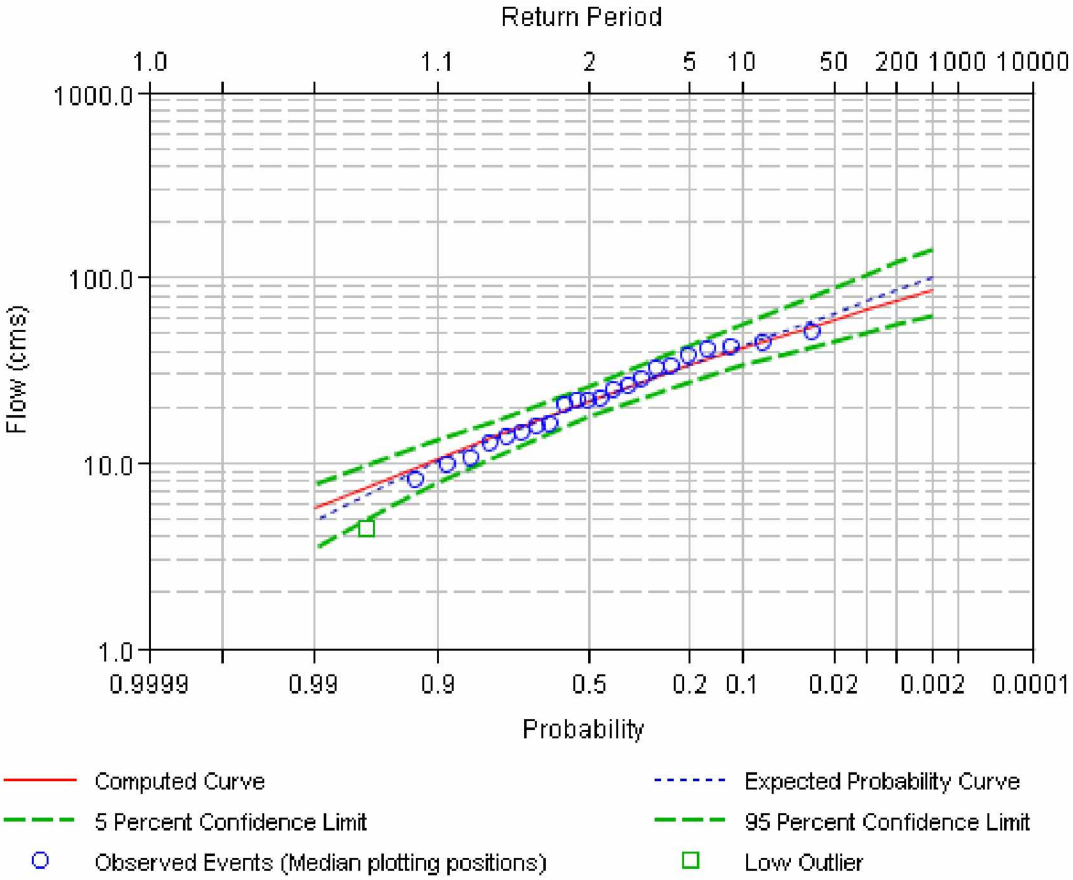

*Figure 10 Bulletin 17B FFA plot for Upper Kuparuk River.*

*Table 4 Flood Frequency Analysis results for Upper Kuparuk River at Alyeska pipeline crossing.*

| | Historical Peak Flows with Bulletin 17B | | | | 2016 USGS Equations ($m^3$/s) | 2003 USGS Equations ($m^3$/s) |
|---|---|---|---|---|---|---|
| Chance Exceedance (%) | Computed Curve Flow ($m^3$/s) | Expected Probability Flow ($m^3$/s) | Confidence Limits Flow ($m^3$/s) | | | |
| | | | 5% | 95% | | |
| 0.2 | 85.5 | 101.2 | 141.5 | 61.9 | 49.27 | 104.1 |
| 0.5 | 75.1 | 85.5 | 119.6 | 55.6 | 41.54 | 92.9 |
| 1 | 67.3 | 74.6 | 103.8 | 50.7 | 35.97 | 84.2 |
| 2 | 59.5 | 64.4 | 88.7 | 45.7 | 30.58 | 75.4 |
| 4 | | | | | 25.51 | 66.3 |
| 5 | 49.3 | 51.9 | 69.7 | 38.9 | | |
| 10 | 41.5 | 42.8 | 56.1 | 33.5 | 19.03 | 53.8 |
| 20 | 33.4 | 34 | 43 | 27.5 | 14.30 | 43.7 |
| 50 | 21.7 | 21.7 | 26.2 | 18 | 8.27 | 28.2 |
| 80 | 13.7 | 13.4 | 16.6 | 10.6 | | |
| 90 | 10.6 | 10.2 | 13.2 | 7.8 | | |
| 95 | 8.6 | 8 | 11 | 5.9 | | |
| 99 | 5.6 | 4.9 | 7.7 | 3.5 | | |

The FFA results for the Upper Kuparuk River (Table 4) shows several important things. The peak flows estimated with the 2016 USGS equations are lower than even the confidence limit of 95%. The 2016 USGS equations are roughly ½ the AEP flow from the historical data. The 2003 USGS equations solve for the same chance exceedance probabilities as the 2016 USGS equations, but the magnitude of peak flows is greater.

### 5.2.2 Putuligayuk River

The Putuligayuk River (Figure 11) does not have as many observed peak flow events as Upper Kuparuk River (n = 17) (Figure 10). This is because WERC monitoring of the Putuligayuk River started later than the monitoring at the Upper Kuparuk River, however the USGS has been recording flow since the 1970's.

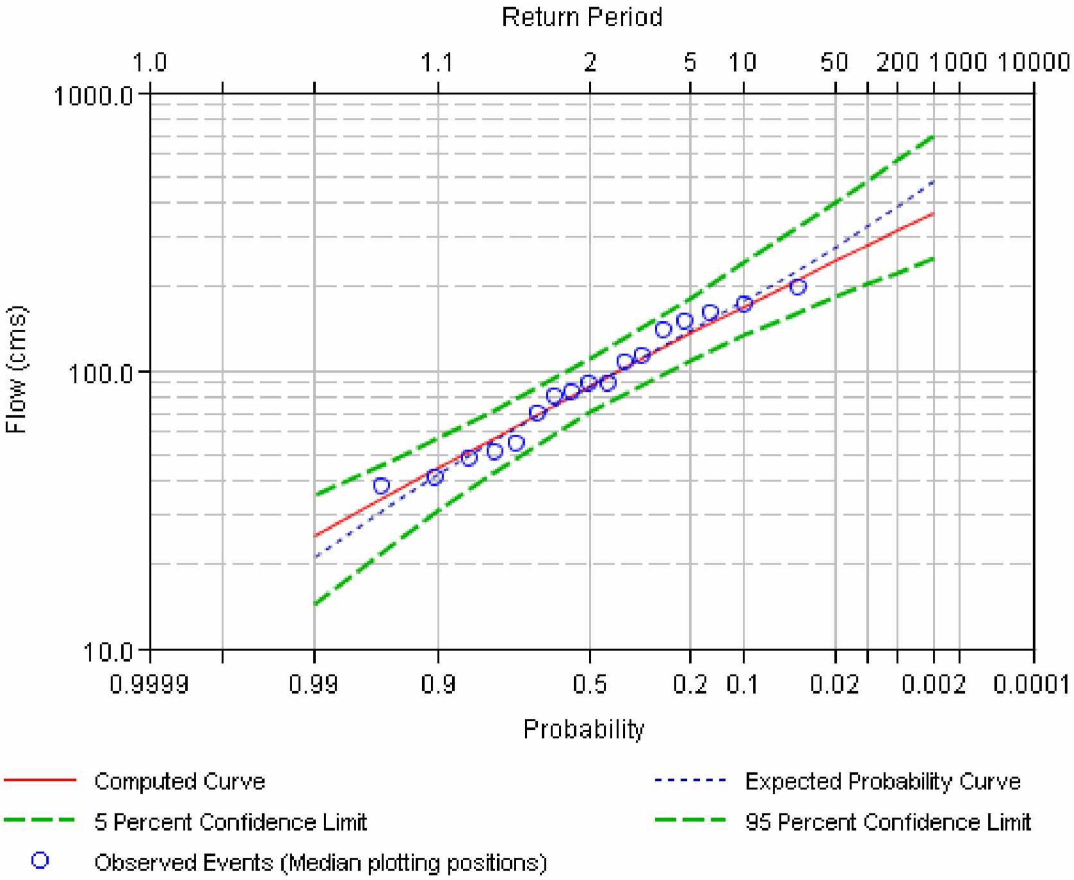

*Figure 11 Bulletin 17B FFA plot for Putuligayuk River.*

The FFA results for Putuligayuk River (Table 5) suggests the larger the peak flow, the greater the divide between AEP flows calculated from historical data and the USGS equations. For the 50-year flood, ($Q_{50\text{-yr}}$) the 2016 USGS equation has 30.9 $m^3/s$, while the historical data analysis $Q_{50\text{-yr}}$ is 278.7 $m^3/s$. Generally, the 2016 USGS equations predict lower peak flows for given AEP. The 2003 USGS equations have higher peak flows for given AEP than the 2016 USGS equations. However, the 2003 USGS results are still lower than the curve computed from observed peak flows. The Putuligayuk River has the largest peak flows out of all four watersheds. It also has the largest area and the lowest slope.

*Table 5 Flood Frequency Analysis results for Putuligayuk River near Spine Road.*

| | Historical Peak Flows with Bulletin 17B | | | | 2016 USGS Equations Q ($m^3$/s) | 2003 USGS Equations Q ($m^3$/s) |
|---|---|---|---|---|---|---|
| Chance Exceedance (%) | Computed Curve Flow ($m^3$/s) | Expected Probability. Flow ($m^3$/s) | Confidence Limits Flow ($m^3$/s) | | | |
| | | | 5% | 95% | | |
| 0.2 | 367.8 | 482.7 | 695.7 | 253.5 | 51.77 | 280.34 |
| 0.5 | 318.3 | 390.7 | 570.2 | 225.5 | 43.10 | 251.85 |
| 1 | 282.2 | 331.1 | 483.6 | 204.5 | 36.89 | 229.77 |
| 2 | 247.2 | 278.7 | 403.8 | 183.4 | 30.97 | 207.04 |
| 4 | | | | | 25.37 | 183.47 |
| 5 | 202.3 | 218 | 308 | 155.1 | | |
| 10 | 168.9 | 177 | 242.5 | 132.9 | 18.34 | 150.67 |
| 20 | 135.5 | 138.8 | 182.3 | 109.1 | 13.34 | 123.81 |
| 50 | 88.1 | 88.1 | 109.4 | 71 | 7.18 | 82.23 |
| 80 | 56.7 | 55.2 | 70.3 | 42.1 | | |
| 90 | 44.8 | 42.6 | 57 | 31.1 | | |
| 95 | 36.8 | 33.9 | 48.2 | 24 | | |
| 99 | 25.4 | 21.1 | 35.4 | 14.5 | | |

### 5.2.3 Imnavait Creek

Imnavait Creek has many observed events and therefore has narrow confidence intervals. There are 29 observed (peak) events with no outliers. The more observed events, the smaller the 95 % confidence intervals become.

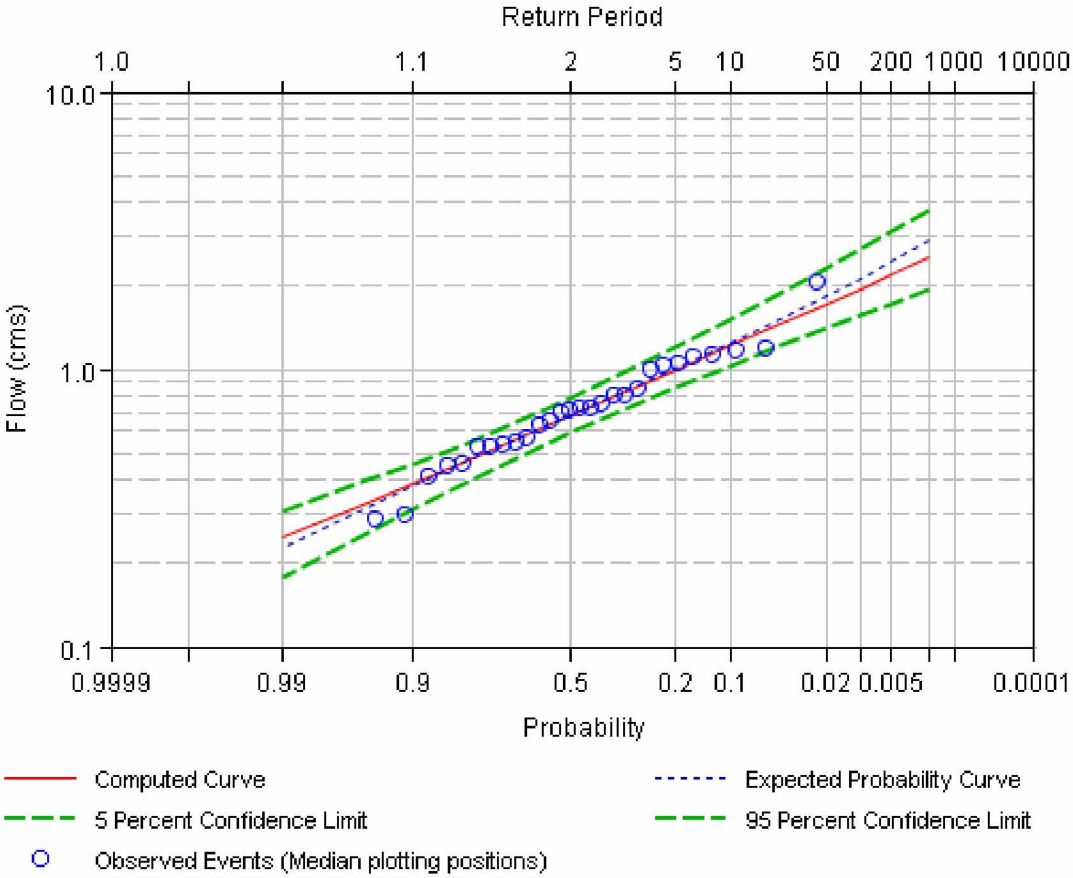

*Figure 12 Bulletin 17B FFA plot for Imnavait Creek*

The FFA for Imnavait Creek (Table 6) shows a 50-year flood for Bulletin 17B, a expected flow of 2.0 $m^3/s$. In the 2016 USGS equations, the 50-year flood has a peak discharge of 1.2 $m^3/s$ and 2003 USGS equations show a 50-year flood of 2.25 $m^3/s$. 2016 USGS equations are underestimating peak flows when compared to the Bulletin 17B FFA, while the 2003 USGS equations are relatively close to the FFA computed flow. Imnavait Creek being the smallest watershed, shows a 50-year flood, or a 2% chance exceedance of 2.0 $m^3/s$ with a 5% confidence interval (or confidence limit) of 2.5 $m^3/s$ to a 95% confidence interval of 1.5 $m^3/s$. While this is a smaller watershed, and the difference between the 2016 USGS equations and historical FFA is of a smaller discrepancy, the 2016 USGS equations are still continually less than the HEC-SSP predicted flows. The 2003 USGS equations and the historical FFA are very similar, with the 2003 USGS equations predicting slightly higher peak flows.

*Table 6 Flood Frequency Analysis results using Bulletin 17B, the 2003 and 2016 USGS equations for Imnavait Creek.*

| | Historical Peak Flows with Bulletin 17B | | | | 2016 USGS Equations ($m^3/s$) | 2003 USGS Equations ($m^3/s$) |
|---|---|---|---|---|---|---|
| Chance Exceedance (%) | Computed Curve Flow ($m^3/s$) | Expected Probability Flow ($m^3/s$) | Confidence Limits Flow ($m^3/s$) | | | |
| | | | 5% | 95% | | |
| 0.2 | 2.7 | 3.1 | 4.0 | 2.0 | 2.2 | 3.32 |
| 0.5 | 2.3 | 2.6 | 3.4 | 1.8 | 1.8 | 2.89 |
| 1.0 | 2.1 | 2.3 | 2.9 | 1.7 | 1.5 | 2.57 |
| 2.0 | 1.8 | 2.0 | 2.5 | 1.5 | 1.2 | 2.25 |
| 4.0 | | | | | 0.9 | 1.93 |
| 5.0 | 1.5 | 1.6 | 2.0 | 1.3 | | |
| 10.0 | 1.3 | 1.3 | 1.6 | 1.1 | 0.6 | 1.5 |
| 20.0 | 1.0 | 1.1 | 1.3 | 0.9 | 0.4 | 1.17 |
| 50.0 | 0.7 | 0.7 | 0.8 | 0.6 | 0.2 | 0.69 |
| 80.0 | 0.5 | 0.5 | 0.6 | 0.4 | | |
| 90.0 | 0.4 | 0.4 | 0.5 | 0.3 | | |
| 95.0 | 0.3 | 0.3 | 0.4 | 0.3 | | |
| 99.0 | 0.3 | 0.2 | 0.3 | 0.2 | | |

### 5.2.4 Roche Moutonnée Creek

Roche Moutonnée Creek historical peak flows are shown on Figure 13 as blue circles. Similar to previous graphs, Log-Pearson Type III computed curve is shown in red and confidence intervals are plotted in dashed green line.

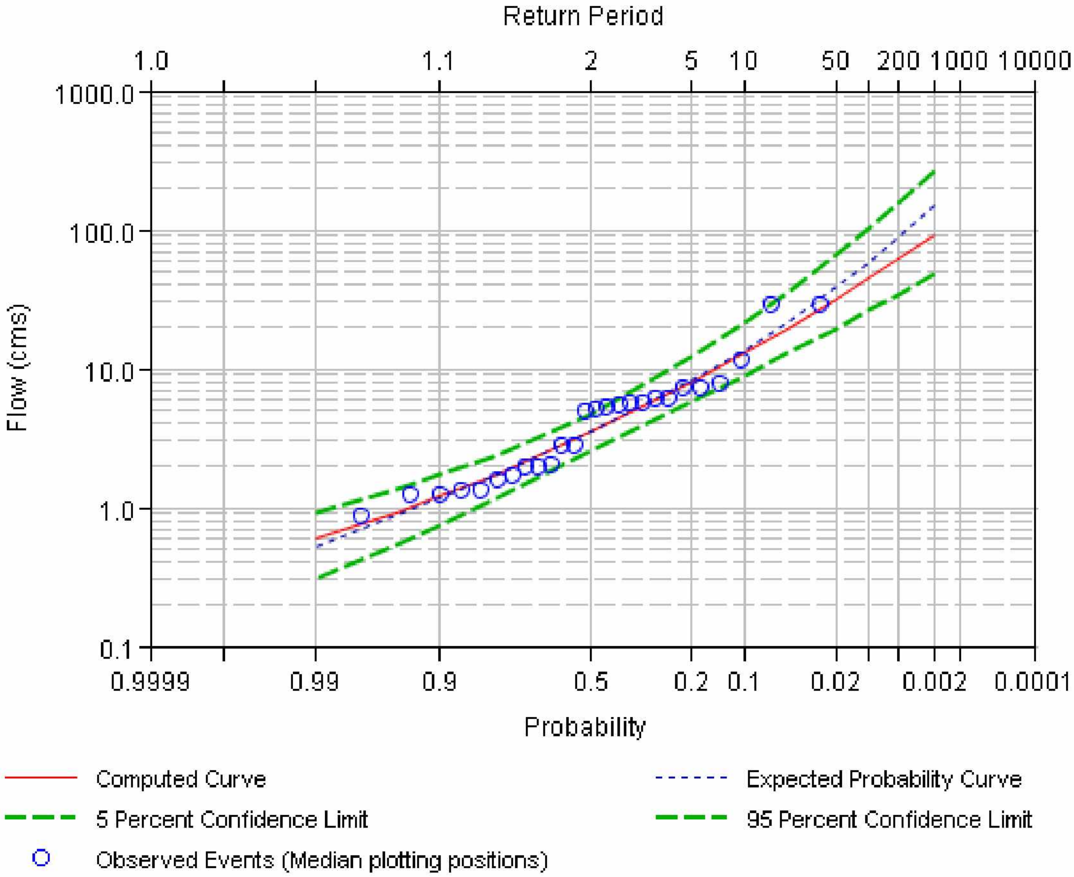

*Figure 13 Bulletin 17B FFA plot for Roche Moutonnée Creek*

For Roche Moutonnée Creek, the 2016 and 2003 USGS equations have larger estimated peak discharges than Bulletin 17B analysis based on historical peak flow data. Table 7 shows the 50-yr flood ($Q_{50\text{-yr}}$) calculated from historical data of 23.2 m$^3$/s, for the statistical 2016 USGS equation, $Q_{50\text{-yr}}$ is 40.2 m$^3$/s, almost half as much. For the 2003 equation, the $Q_{50\text{-yr}}$ flow was 48.35 m$^3$/s. Larger floods, $Q_{100\text{-yr}}$ and larger are underestimated, but smaller floods are overestimated with the 2016 and 2003 USGS equation (Table 7).

*Table 7 Flood Frequency Analysis results for Roche Moutonnée Creek.*

| | Historical Peak Flows with Bulletin 17B | | | | 2016 USGS Equations (m$^3$/s) | 2003 USGS Equations (m$^3$/s) |
|---|---|---|---|---|---|---|
| Chance Exceedance (%) | Computed Curve Flow (m$^3$/s) | Expected Probability Flow (m$^3$/s) | Confidence Limits Flow (m$^3$/s) | | | |
| | | | 5% | 95% | | |
| 0.2 | 57.3 | 88.0 | 145.4 | 31.6 | 62.3 | 67.42 |
| 0.5 | 40.8 | 55.7 | 93.7 | 23.8 | 53.3 | 59.98 |
| 1.0 | 31.0 | 39.3 | 65.9 | 19.0 | 46.7 | 54.28 |
| 2.0 | 23.2 | 27.5 | 45.4 | 14.9 | 40.2 | 48.45 |
| 4.0 | | | | | 34.2 | 42.48 |
| 5.0 | 15.2 | 16.8 | 26.6 | 10.4 | | |
| 10.0 | 10.6 | 11.3 | 16.9 | 7.6 | 26.3 | 34.28 |
| 20.0 | 7.0 | 7.2 | 10.2 | 5.2 | 20.4 | 27.67 |
| 50.0 | 3.3 | 3.3 | 4.4 | 2.5 | 12.6 | 17.68 |
| 80.0 | 1.7 | 1.6 | 2.3 | 1.1 | | |
| 90.0 | 1.2 | 1.2 | 1.7 | 0.8 | | |
| 95.0 | 0.9 | 0.9 | 1.3 | 0.6 | | |
| 99.0 | 0.6 | 0.5 | 0.9 | 0.3 | | |

5.2.5 Comparison of FFA methods between watersheds

The 2-yr flood comparison (Table 10) shows the 2003 USGS equations to be close to the Bulletin 17B estimates except for Roche Moutonnée Creek. Imnavait Creek shows the same estimated peak flow (0.7 $m^3/s$) for Bulletin 17B and the 2003 USGS equation. The 2016 USGS equation are the lowest of the peak flow estimates except for Roche Moutonnée Creek. For the 2-yr flood discharge estimate, Bulletin 17B has the lowest estimated peak flow for Roche Moutonnée Creek.

*Table 8 2-yr flood comparing the peak discharge estimates of different FFA methods.*

| 2-yr Peak Discharge Estimates ($m^3/s$) | | | | |
|---|---|---|---|---|
| | Upper Kuparuk River | Putuligayuk River | Imnavait Creek | Roche Moutonnée Creek |
| Bulletin 17B | 21.7 | 88.1 | 0.7 | 3.3 |
| 2003 USGS | 28.2 | 82.2 | 0.7 | 17.7 |
| 2016 USGS | 8.3 | 7.2 | 0.2 | 12.6 |

The 10-yr flood comparison (Table 9) shows Bulletin 17B to estimate smaller peak discharges than the 2003 USGS equations apart from the Putuligayuk River estimation. 2016 USGS equations are the lowest estimates for peak flow for all four watersheds.

*Table 9 10-yr flood comparing the peak discharge estimates of different FFA methods.*

| 10-yr Peak Discharge Estimates ($m^3/s$) | | | | |
|---|---|---|---|---|
| | Upper Kuparuk River | Putuligayuk River | Imnavait Creek | Roche Moutonnée Creek |
| Bulletin 17B | 42.8 | 177 | 1.3 | 11.3 |
| 2003 USGS | 53.8 | 150.7 | 1.5 | 34.3 |
| 2016 USGS | 19 | 18.3 | 0.6 | 26.3 |

The 100-yr flood comparison (Table 10) shows the 2016 USGS equation is the lowest of all FFA methods. While 2016 USGS equation for the Putuligayuk River for a 100-yr flood estimates peak flow to be 36.9 m$^3$/s, Bulletin 17B estimates 331.1 m$^3$/s and the 2003 USGS equation estimates it to be 229.8 m$^3$/s. Both Bulletin 17B and the 2003 USGS equation estimates are larger by an order of magnitude.

*Table 10 100-yr flood comparing the peak discharge estimates of different FFA methods.*

| 100-yr Peak Discharge Estimates (m$^3$/s) | | | | |
|---|---|---|---|---|
| | Upper Kuparuk River | Putuligayuk River | Imnavait Creek | Roche Moutonnée Creek |
| Bulletin 17B | 74.6 | 331.1 | 2.3 | 39.3 |
| 2003 USGS | 84.2 | 229.8 | 2.6 | 54.3 |
| 2016 USGS | 36 | 36.9 | 1.5 | 46.7 |

### 5.3 Linear Regression Analysis

#### 5.3.1 Simple linear regression analysis

The results of simple linear regression analysis are summarized in a set of plots (Figure 13-Figure 16). The analysis starts with single watersheds. Each set of boxplots represents a watershed and all the independent variables available for that watershed. The following figures show every variable compared with each other. The correlation coefficient (r) is used to suggest the strength of the relationship between $x_i$ and $y_i$ (Weisberg 2014). Correlation coefficients (r) are placed in every corresponding graph to show possible relation. Graphs with an '*' in the corner denote r values that come from variables missing data points. All variables have 10 or more data points to be included in the regression analysis. Correlation coefficient (r) = 1 or -1 shows perfect correlation.

##### 5.3.1.1 Upper Kuparuk River

The following variables are analyzed in the Upper Kuparuk watershed: peak discharge $Q_p$ (m$^3$/s); normalized peak discharge $q_p$ (m$^3$/s/km$^2$); SWE (cm); precipitation P (cm); length of melt (LoM), the number of days for the snow to completely melt; rainfall $P_R$ (cm).

Rainfall is different from P as total precipitation included rainfall as well as snow. Length of melt, SWE, rainfall and precipitation data are the independent variables without a full dataset.

Interannual variation in SWE explained 53.7 % ($R^2 = 0.537$, $p < 0.001$) of the variation in $Q_p$ over the period of record in the Upper Kuparuk Watershed, according to the linear regression equation using just SWE to predict $Q_p$. Other compared variables with high correlation coefficients are LoM and precipitation ($r = 0.890$) and precipitation and rainfall ($r = 0.907$) (Figure 13). The correlation between precipitation and rainfall is understandable, as precipitation is not independent from rainfall. The correlation between year and SWE is shown, but that is not considered to be a true correlation. Time cannot be used as an indication of trend as time never goes backwards in response to an independent variable, it is just a marker so therefore this correlation is just correlation, not causation.

Having found the high correlations, the few independent variables are used to run a linear regression analysis. The linear regression equation analysis for Upper Kuparuk watershed's SWE and precipitation explained 55.7% of the interannual variation in peak discharge, with a p-value of 0.003. This p-value is greater than the p-value for the simple linear regression equation using the independent variable of SWE. The linear regression equation for peak discharge with SWE as a variable has an $R^2$ value of 53.65%, however the p-value for the SWE variable is less than 0.001, or in other words, is within the 99.99 percentile confidence interval. The linear regression equation for peak discharge with precipitation as the independent variable shows precipitation to be significant.

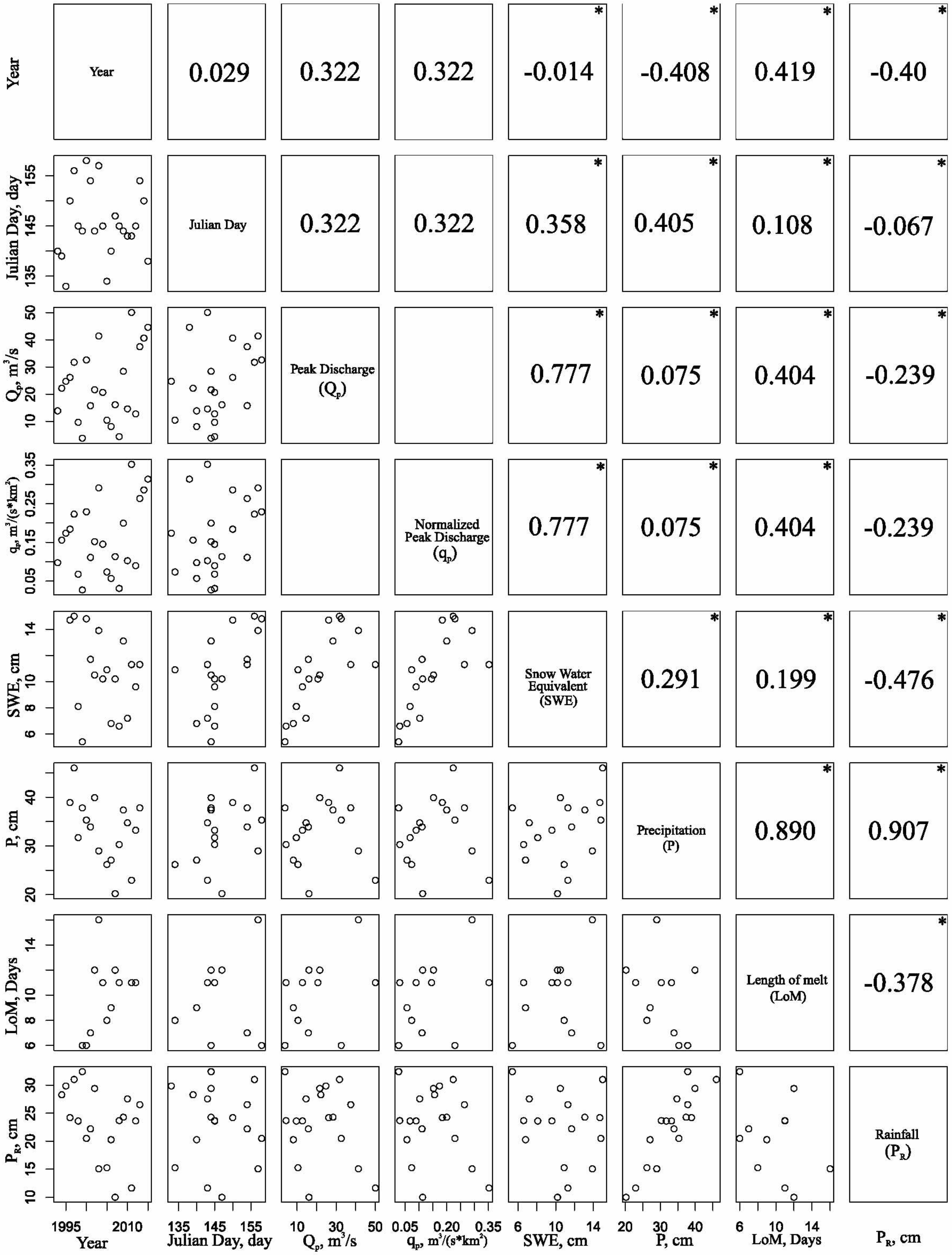

*Figure 14 Comparison of Upper Kuparuk Watershed independent variables. Peak discharge is $Q_P$ ($m^3/s$). Julian day is the day of peak flow. Normalized peak discharge is $q_P$ (m/s). SWE is in centimeters. Rainfall, $P_R$ is centimeters. The numbers in the upper right of the matrix are correlation coefficients (r). The '*' in the corner shows independent variables that do not contain a complete dataset.*

### 5.3.1.2 Putuligayuk River

There are several r values of interest in the single variable comparison shown on Figure 14. Peak discharge and year are not correlated, $r = 0.134$, the linear regression equation supports this ($R^2 = 0.0181$, $p = 0.6067$). Peak discharge and Julian day is also not highly correlated, $r = 0.251$, with the linear regression having an $R^2$ of 0.0628 ($p = 0.3318$). Peak discharge and SWE are also not correlated with $r = 0.208$. Making a linear regression equation with only SWE, the SWE variable has a p-value of 0.357. Peak discharge and storage have a higher correlation coefficient ($r = 0.612$). Peak discharge and previous year's rainfall has a correlation coefficient value of 0.519. Because normalized peak discharge is dependent on peak discharge, that graph would have had an $R^2$ value of 1.

The linear regression equation for storage and peak discharge is not strongly correlated ($R^2 = 0.375$, $p = 0.060$). Other comparisons that show no correlation are peak discharge and SWE ($R^2 = 0.0433$, $p = 0.4566$). But peak discharge and previous year's rainfall ($R^2 = 0.3052$, $p= 0.162$) shows a similar $R^2$ value and a similar p-value to the linear regression of storage and peak discharge. Because storage and rainfall have similar correlation with peak discharge and acknowledging that SWE has high correlations in Imnavait Creek and Upper Kuparuk River, multiple linear regression will be used to see if there is a stronger equation with two variables or more. Storage, SWE and precipitation will be compared.

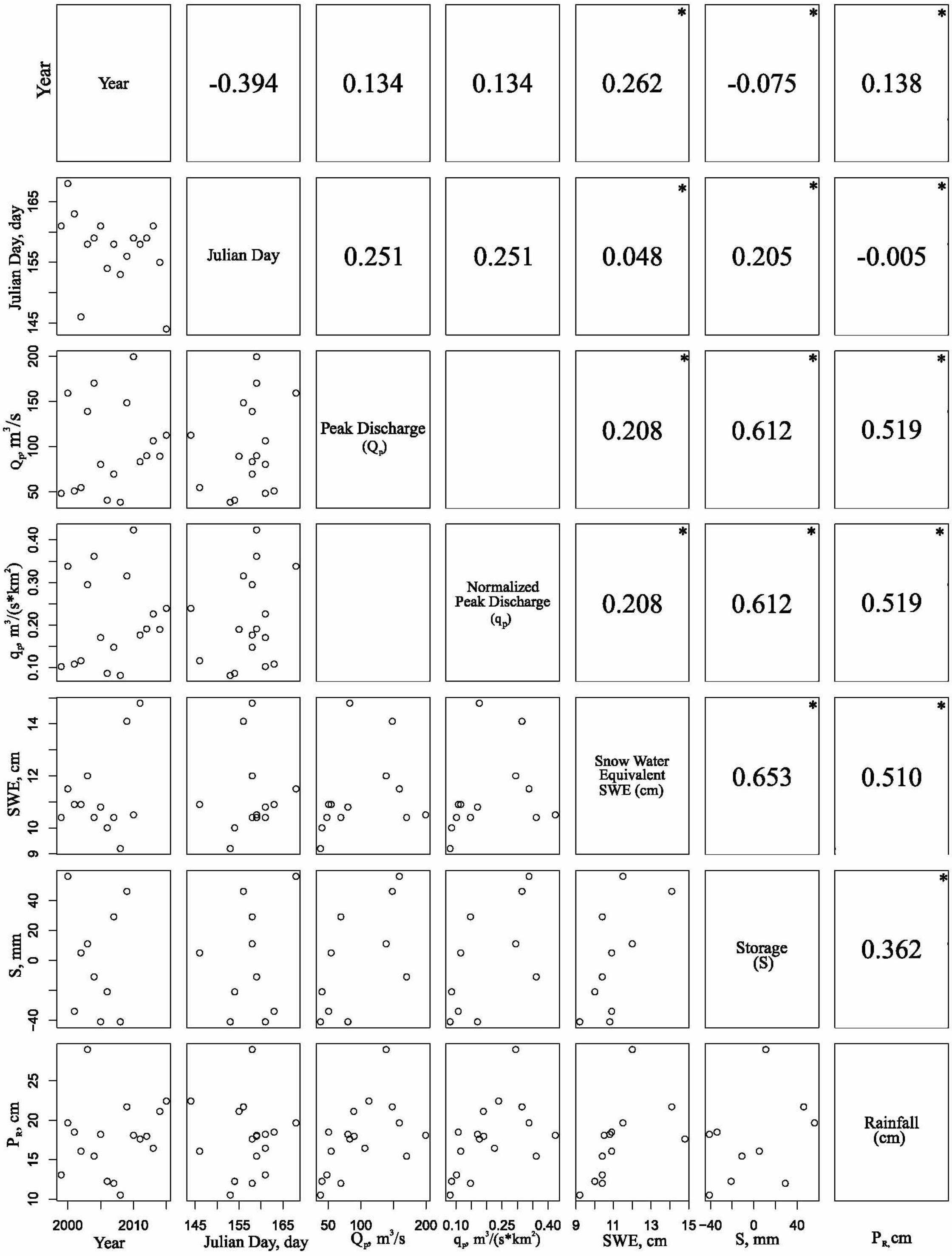

*Figure 15 Comparison of independent variables of the Putuligayuk River Watershed. Year is year of peak discharge. Peak discharge is $Q_P$ ($m^3/s$). Normalized peak discharge is $q_P$, ($m^3/(s*km^2)$). Storage, S, is in millimeters. Precipitation, P, is in centimeters, Rainfall, $P_R$, is in centimeters. SWE is in centimeters. Length of melt, LoM, is in days. Rate of ablation, RoA, is SWE over day. The numbers in the upper right of the matrix are correlation coefficients (r). The '*' in the corner shows independent variables that do not contain a complete dataset.*

### 5.3.1.3 Imnavait Creek

Imnavait is the smallest watershed, it has the smallest peaks, understandable for its catchment area. There is correlation between peak discharge and SWE (Figure 15). It is also evident that rainfall and precipitation have a high correlation ($r = 0.509$). SWE is also indicative of LoM ($r = 0.655$).

Peak discharge and SWE have the highest correlation in the single variable comparison for Imnavait Creek. The linear regression equation for peak discharge and SWE shows a significance for SWE ($R^2 = 0.2115$, $p = 0.0138$). The second point of interest is peak discharge and RoA ($r = -0.380$). The linear regression equation for peak discharge and RoA shows significance in RoA ($R^2 = 0.145$, $p = 0.046$).

RoA and SWE will be combined for a possible multiple linear regression equation.

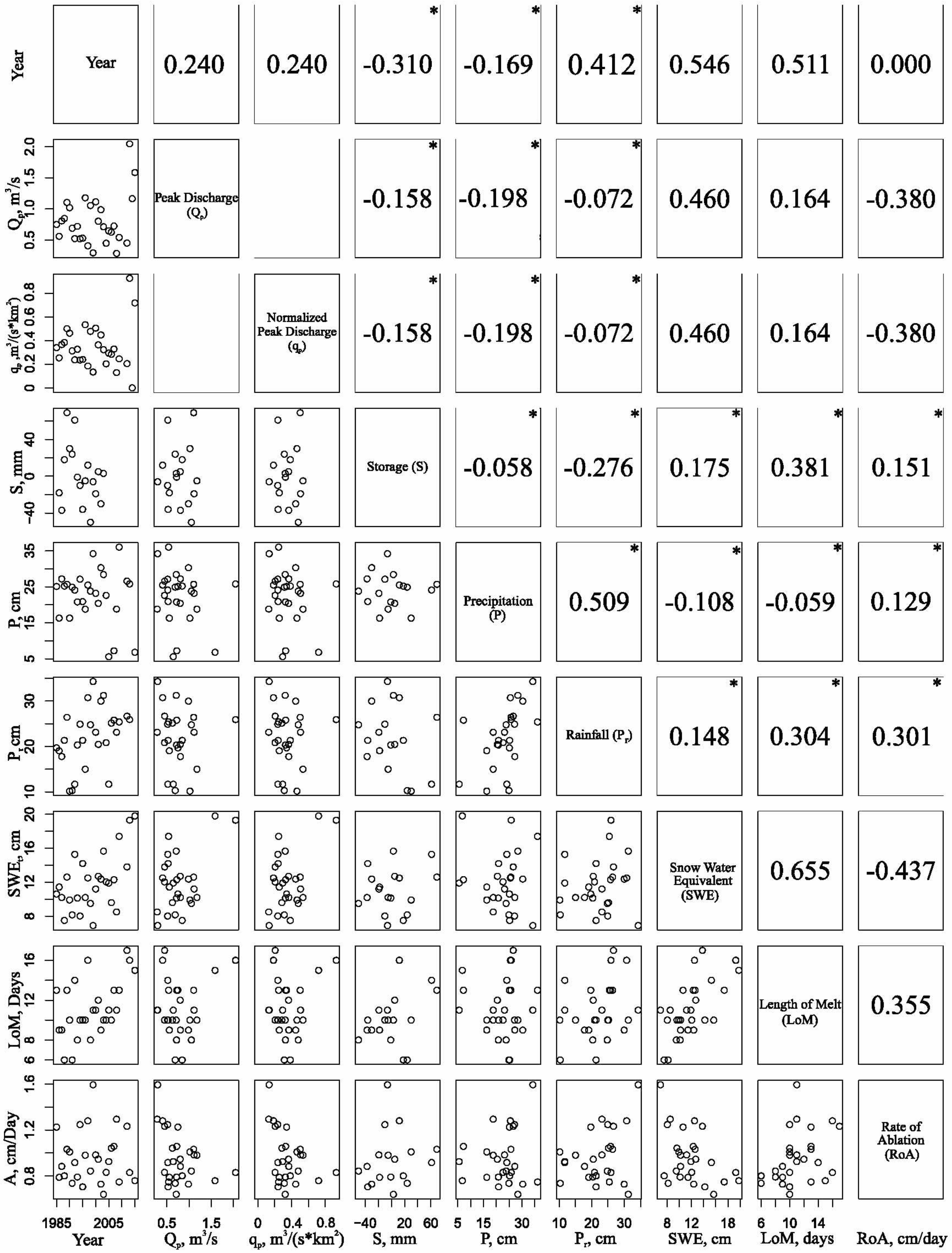

*Figure 16 Comparison of Imnavait Watershed independent variables. Year is year of peak discharge. Peak discharge is $Q_P$, ($m^3/s$), normalized peak discharge, $q_P$, ($m^3/(s*km^2)$), SWE is in centimeters and storage in is millimeters. Precipitation (P) is in centimeter. Rainfall ($P_r$)is in centimeters. Length of Melt (LoM) is the time in days it takes for SWE to become 0. Rate of Ablation (RoA) the rate of how quickly the SWE melted every day (cm/day). The numbers in the upper right of the matrix are correlation coefficients (r). The '*' in the corner shows independent variables that do not contain a complete dataset.*

### 5.3.1.4 All Watersheds

Physiographic factors, such as area or gradient do not change within the period of this study. One question is what independent variable changes year to year and can be a good representative of physiographic watersheds factors. With only four watersheds, true correlation will be hard to prove. Unless more watersheds are added to the study, the results will be limited. Using normalized peak flow (peak flow divided by area) will remove the peak flow dependence on area and illustrate what other factors influence peak flows.

Peak discharge and area have a high correlation coefficient of 0.848. Slope is also correlated to peak discharge ($r = -0.418$) the negative r value means it was inversely correlated. However, that is because larger watersheds in this study have lower slopes, and since area is driver of peak flows it appears that the watersheds with lower slopes have higher peak flows. Slope has an even higher correlation with normalized peak discharge ($r = -0.536$). This is an incorrect relation. A watershed with a steep slope should have a larger peak flow than a watershed of the same size but with a low slope; however, in this linear regression, it is the opposite. Putuligayuk River is the largest and flattest watershed of all four watersheds, and because area is such a strong driver of peak flow, it suppresses any other influence, therefore, even if a steep slope has a positive correlation, that influence is not seen in my correlation coefficients or any linear regression equation.

There seems to be correlation between normalized peak flow and SWE ($r = 0.416$). Therefore, SWE will be tested in a simple linear regression equation as SWE has been proven to be correlated when comparing single watersheds. If there were more data points for storage, it might have a better correlation as well ($r = -0.274$). The simple linear regression for peak discharge and slope has an $R^2$ value of 0.175 ($p < 0.001$).

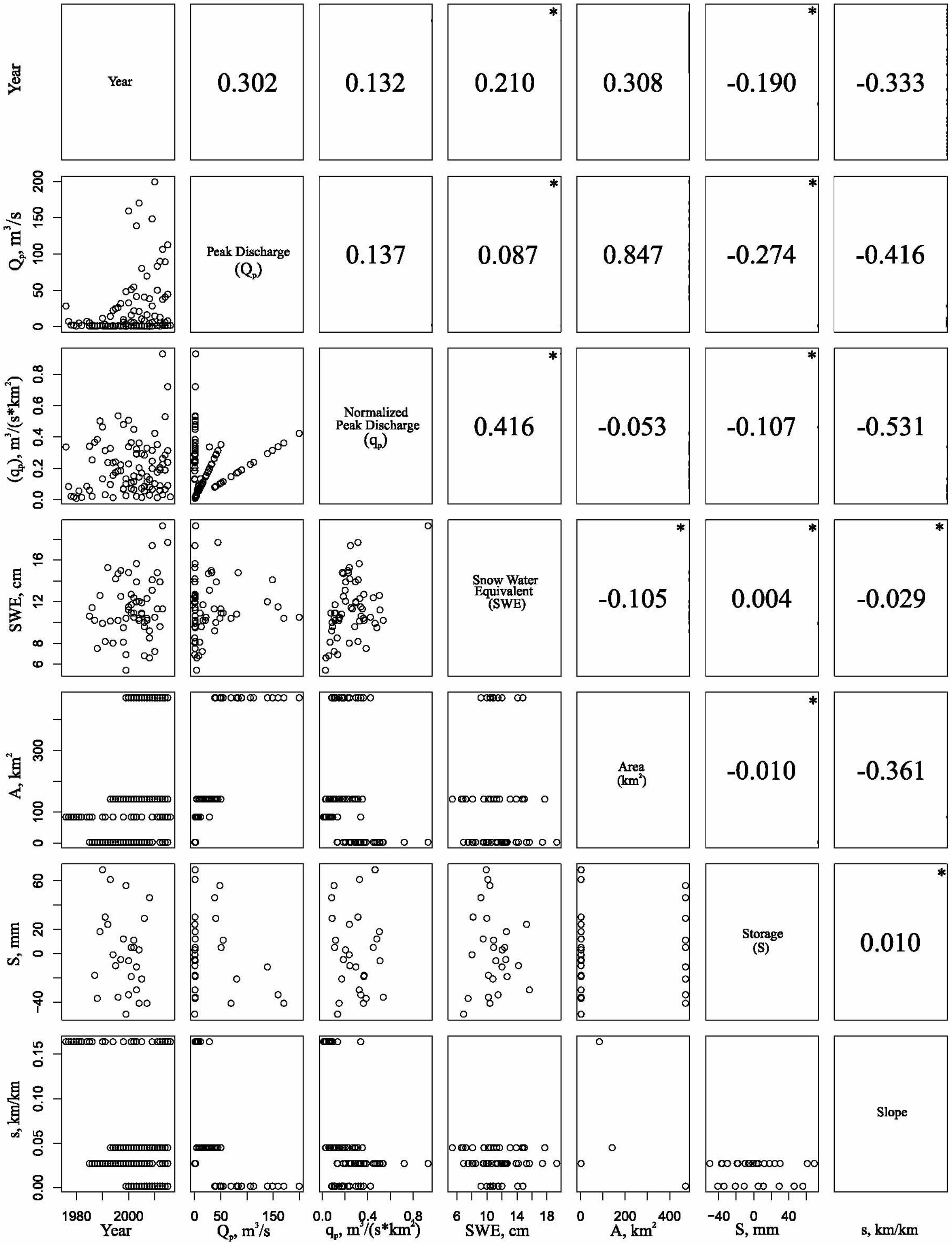

*Figure 17 Comparison of independent variables of all study watersheds. Year is year of peak flow. Peak discharge is $Q_P$ ($m^3/s$), normalized peak discharge is $q_P$ ($m^3/(s*km^2)$), SWE is in centimeters, A is area ($km^2$) Storage is in millimeters, slope is km/km. The numbers in the upper right of the matrix are correlation coefficients (r). The '*' in the corner shows independent variables that do not extend the full dataset.*

5.3.1.5 SWE Frequency Analysis

A different approach to estimating peak discharge by a frequency analysis method would be to create a graph with return periods and an equation that would show the frequency of SWE amounts. Snow Water Equivalent Frequency Analysis (SWEFA) follows the same method as FFA, but uses historic SWE measurements rather than historic peak flows. The SWE given for significant return periods could then be placed into a linear regression equation that uses SWE as a significant independent variable.

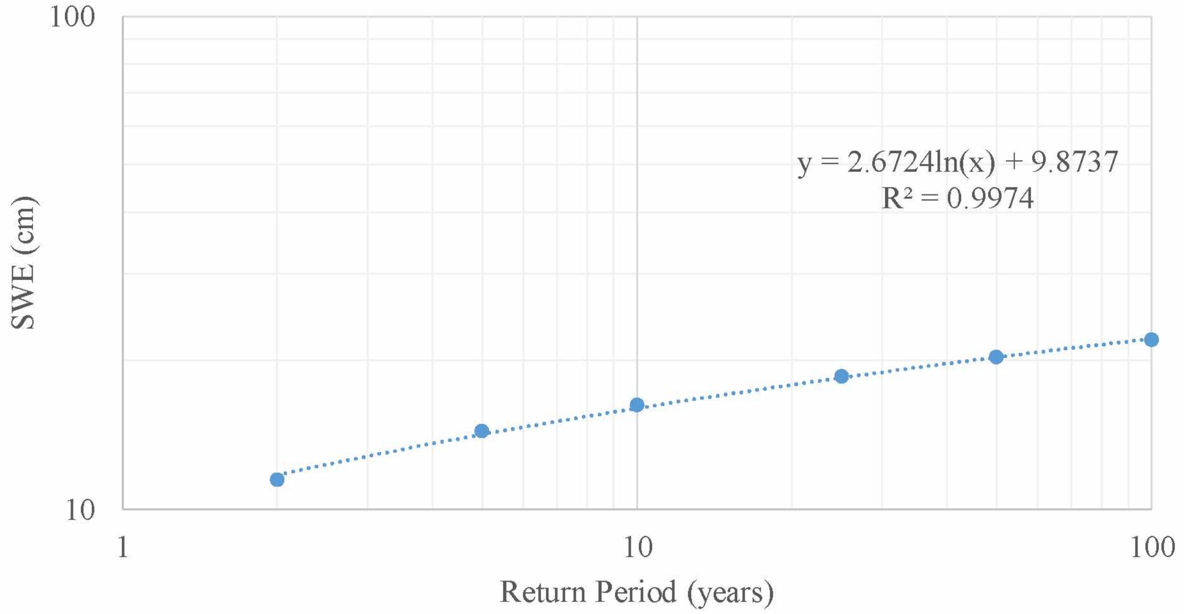

*Figure 18 Imnavait Creek Log-Pearson Type III SWE Frequency Analysis with equation.*

Bulletin 17B uses the Log Pearson Type III method and historic data when determining the FFA, usually the return period gives the magnitude of flood expected. However, in this graph (Figure 17) the return period gives the SWE magnitude. If the linear regression equation uses SWE, then calculating 5-yr SWE, 100-yr SWE could, in turn, be used in the linear regression equation to find the 5-yr, 100-yr flood. If the SWE was used to predict peak flow, then every year before break-up, SWE can be used to get a rough estimate of what magnitude of peak flow might be possible for that year.

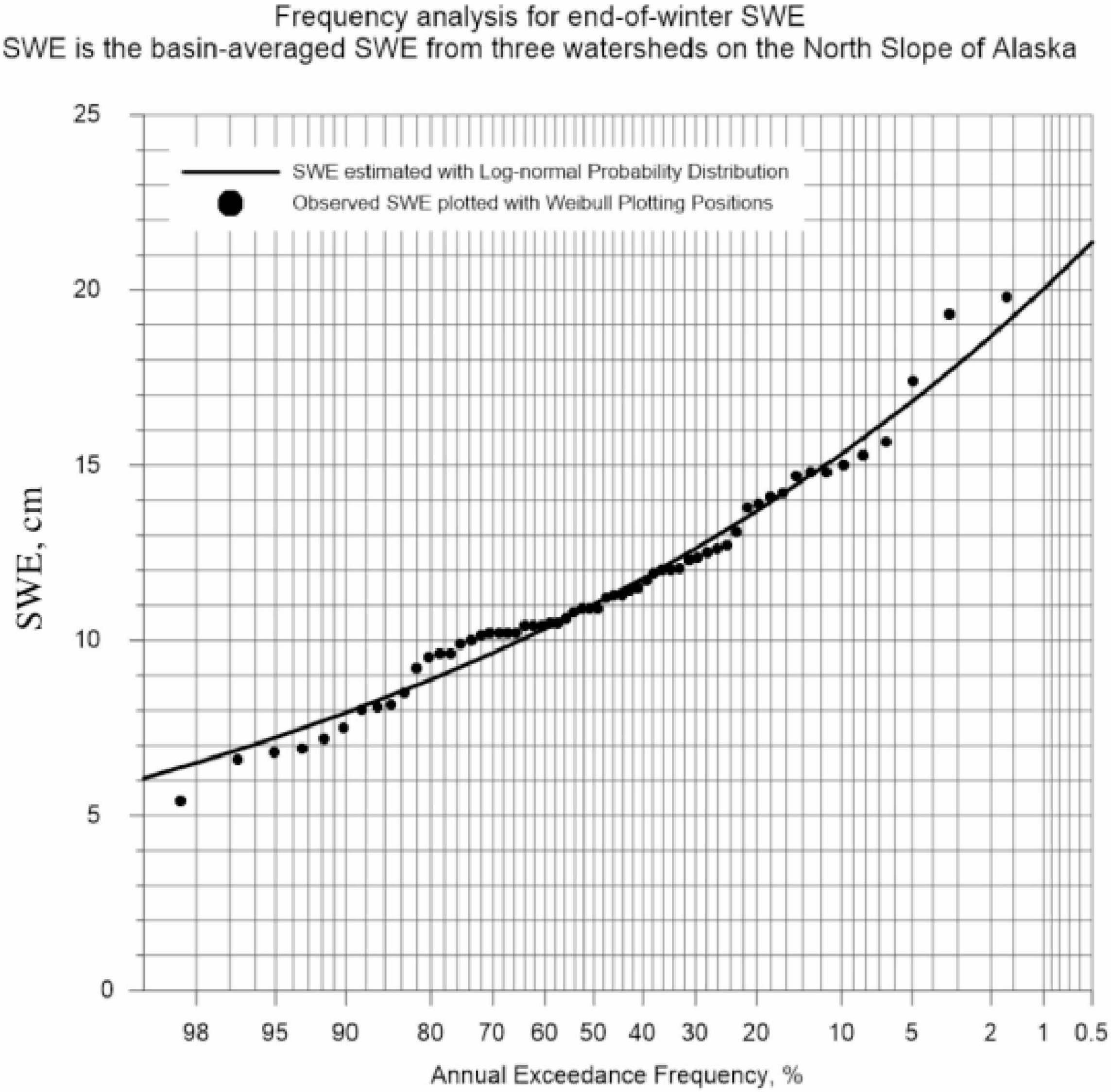

*Figure 19 SWE Frequency Analysis for end-of-winter watershed-averaged SWE using log-normal distribution for 3 watersheds, Imnavait Creek, Upper Kuparuk River and Putuligayuk River. Courtesy of Svetlana Stuefer.*

Combining all three watersheds, Imnavait Creek, Upper Kuparuk River, and the Putuligayuk River together gives more points in which to create a SWEFA. The increased historic SWE data points will only lead to a better equation.

### 5.3.2 Simple or multiple linear regression equations

#### 5.3.2.1 Upper Kuparuk River

The simple linear regression for normalized peak discharge and slope has an $R^2$ value of 0.287 with a significant p-value ($p < 0.001$). The simple linear regression for peak discharge and SWE has a p-value of less than 0.001 ($R^2 = 0.678$). SWE will be included in multiple linear regression as Imnavait Creek and Upper Kuparuk River peak flows show high correlation with it.

Once all three watersheds were compared, by simple linear regression, and then summed together to compare landscape characteristics by simple linear regression, multiple variables were added together to try and create more accurate equations. Combining precipitation with SWE in a multiple linear regression equation show that only SWE has significance, while precipitation does not ($R^2 = 0.4752$, $p = 0.011$), with a lower $R^2$ and a larger p-value, it is not the best linear regression equation for Upper Kuparuk River. Thus, the equation that would best represent the Upper Kuparuk peak flow would be a simple linear regression using the independent variable of SWE.

$$Q_p = 3.272SWE - 13.352 \tag{8}$$

where $Q_P$ is peak discharge ($m^3/s$) and SWE is in centimeters. This equation is applicable only for SWE > 4.0 cm.

#### 5.3.2.2 Putuligayuk River

With multiple linear regression, there will be more than one variable to compare to peak discharge. With a high r, $P_R$ is one of the two independent variables in the linear regression equation. Using SWE to predict peak flows give no significant p-values. However, using precipitation and storage together in a multiple linear regression equation has a smaller $R^2$ value than that from the simple linear regression with storage.

Thus, the best linear regression equation for predicting peak flows at Putuligayuk River would be a simple linear regression.

$$Q_p = 4.13P_R + 0.684S + 23.529 \tag{9}$$

where $Q_P$ is peak discharge ($m^3/s$), $P_R$ is previous year's rainfall (cm) and S is storage (mm).

### 5.3.2.3 Imnavait Creek

The simple linear regression of peak discharge and SWE give an $R^2$ value of 0.21 ($p = 0.0138$). That is a higher $R^2$ value than each simple linear regression equation so a better predictor of peak flows in Imnavait is a multiple linear regression equation using SWE.

$$Q_p = 0.053SWE - 0.147 \tag{10}$$

where $Q_P$ is peak discharge ($m^3/s$) and SWE is in centimeters.

### 5.3.2.4 All Watersheds

A multiple linear regression for peak discharge using the independent variables of area and slope show an $R^2$ value of 0.7341 ($p < 0.005$).

$$Q_p = 0.21660A - 5.67748 \tag{11}$$

where $Q_P$ is peak discharge ($m^3/s$), A is area ($km^2$). The equation is not applicable for watersheds > 27 $km^2$, as the equation will give a negative peak discharge.

This equation only has landscape characteristics and therefore the peak discharge will not change, it would not be a useful predictor of annual peak flows. However, the linear regression equation included Roche Moutonnée Creek, which has been excluded from any linear regression models in this study thus far. Any meteorological data included in a linear regression equation would remove Roche Moutonnée Creek from the analysis, because since the meteorological station was only added in 2015, two years of data does not have any statistical significance, 10 points of data are needed to produce a statistically significant equation.

### 5.3.3 Multiple linear regression

Thus, another equation (Eq. 12) was created to include meteorological data. The $R^2$ value is lower than Equation 9, ($R^2 = 0.6827$, $p < 0.05$), which is still a good $R^2$ value. Including SWE will allow the peak discharge to change annually. Storage was also tested, but could not produce a reliable linear regression equation as Upper Kuparuk River and Roche Moutonnée Creek do not have storage data.

$$Q_p = 2.169SWE + 0.211A - 27.005 \tag{12}$$

where $Q_p$ is peak discharge ($m^3/s$), SWE is end of snow water equivalent (cm), A is watershed area ($km^2$). Assuming a SWE of 10.46 cm, which is a 2-yr SWEFA estimate for all watersheds combined, then a watershed area must be greater than 21 $km^2$.

# Chapter 6 Discussion

The best way to estimate design peak flows is using historic peak flows and flood frequency analysis. Bulletin 17B and Bulletin 17C continues to be the standard for estimating peak discharge frequency accurately. However, in cases of ungauged watersheds, historic peak flows are unknown and other methods such, USGS regression equations, are often used. Accurate peak discharge equations for ungauged watersheds are extremely important when designing hydraulic structures near ungauged watersheds.

Comparing the 2003 and 2016 USGS equations results to historical peak flow analysis with HEC-SSP Bulletin 17B results shows the 2016 USGS equations tend to underestimate the historic peak flows except in the case of Roche Moutonnée Creek, while the 2003 USGS equation overestimated peak discharge, with the exception of the Putuligayuk River (Table 8-10). The 2003 USGS equations were closer to the Bulletin 17B estimates than the 2016 USGS equations.

However, minimal data availability, sparse observational network and short length of record in North Slope of Alaska and Arctic region in general, provide limitations for modeling. The 2016 and 2003 USGS equations make estimating the AEP streamflow magnitude in ungauged watersheds easier and allow more watersheds to be analyzed. The 2016 equations required only two variables and are the same equations for all of Alaska and Northern Canada. While creating one set of equations from many data points is the best approach, the limited amount of gauge data in the far north coupled with multiple gauges concentrated in populated, warmer areas could skewer the equations to be more accurate in warmer areas rather than watersheds situated above the Arctic Circle. The method used in the 2016 USGS report, while statistically strong, did not give the best peak flow estimates because a single region for the entire state is too large to use one equation for an accurate estimation. The 2003 equations only have one variable, watershed area, but only have seven stations to represent the entire region.

Figure 20 shows the simple linear regression equation found for all four watersheds. The average peak discharge was taken from each watershed to illustrate how precise the equation is.

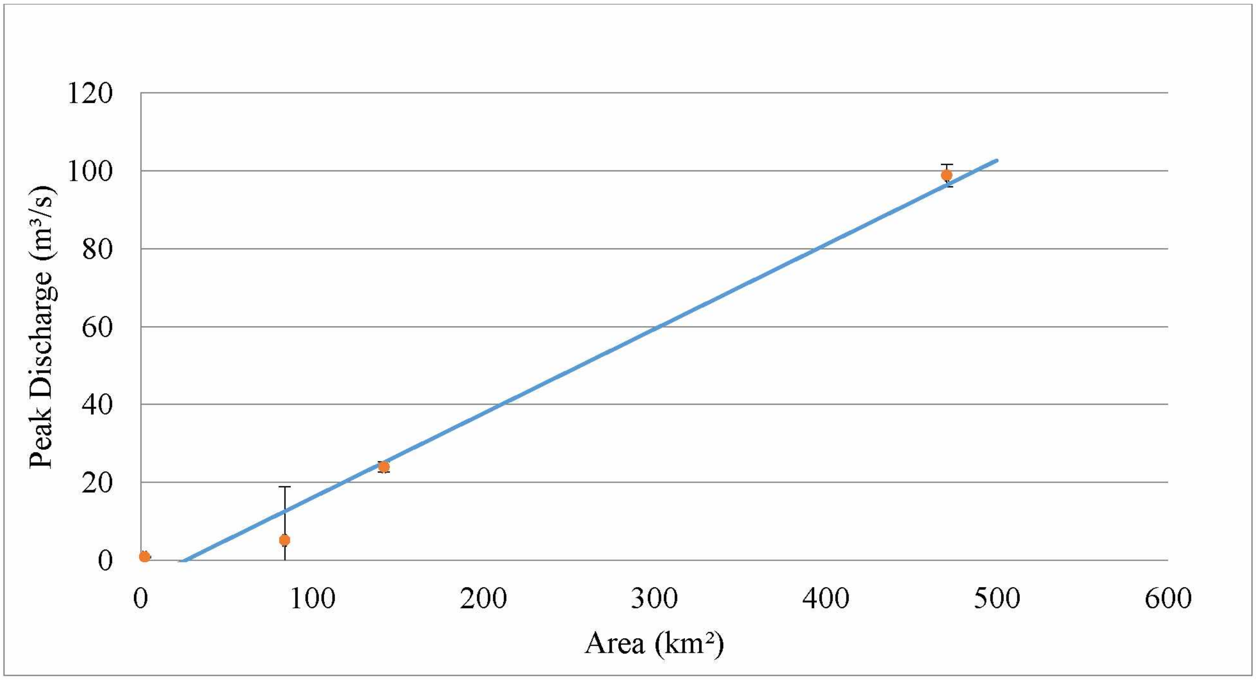

*Figure 20 All Watersheds I linear regression equation line with the average historic peak discharge points and 95% confidence intervals from each watershed.*

Larger watersheds show physiographic factors as the drivers of peak flows. The average peak flow for Putuligayuk River and Upper Kuparuk, both watersheds have area greater than 100km$^2$, fall within the 95% confidence intervals. Streams with smaller watershed area show meteorological factors hold the key to influence peak flows. This will be shown as the linear regression equations for individual watersheds are discussed.

Figure 21 is a graph plotting Equation 12, which has two variables, to show what the range of peak flows might be. SWE is held constant based on SWE frequency analysis. The lower line represents 2-yr SWE and upper line represents 100-yr SWE (which came from Figure 18), from 10.46 cm to 22.01 cm. Area went from 1 $km^2$ to 600 $km^2$, with area increased by increments of 1 $km^{2.}$ The 10-yr SWE and 100-yr SWE, and area were used in Eq. 12, to calculate peak discharge, the 10-yr and 100-yr SWE are represented as blue and orange lines on the graph.

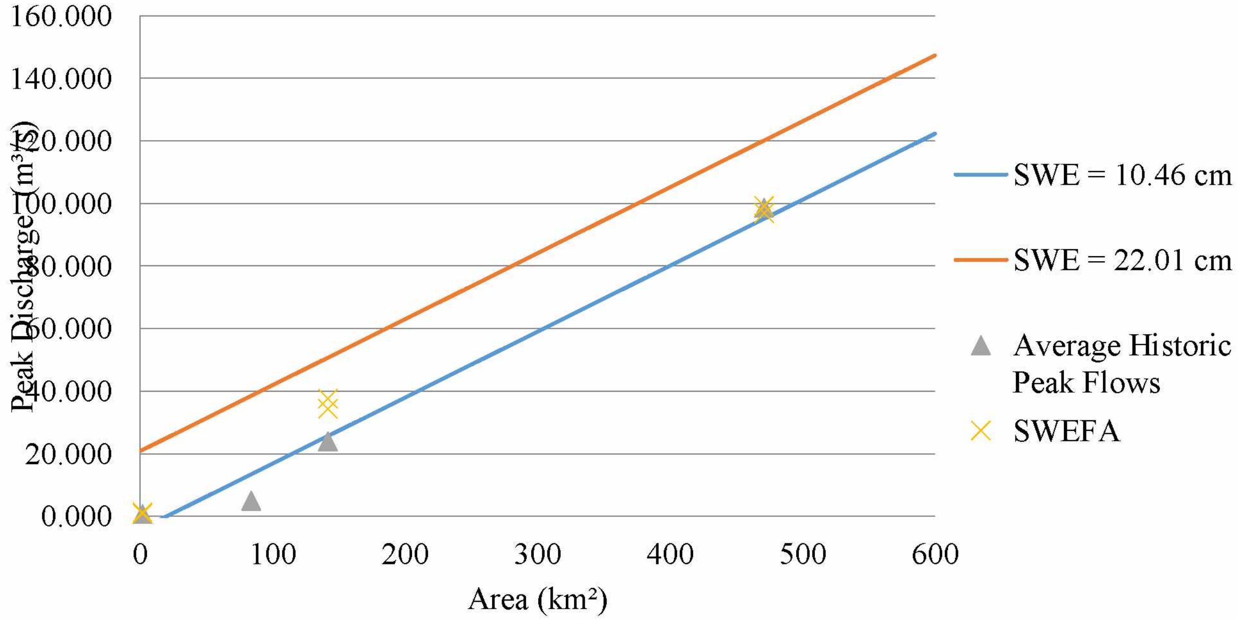

*Figure 21 All watersheds II multiple linear regression equation and average historic peak flows and individual SWE frequency analysis points for 10-year and 100-year SWE.*

The Upper Kuparuk River and Imnavait Creek watersheds have been modeled before, with physical models such as Hydrologiska Byråns Vattenbalansavdelning (HBV) or Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS). This study provides analysis and modeling of peak flow data based on statistical approaches.

The comparison of discharge hydrographs with the specific discharge hydrographs shows that area is a major factor that controls magnitude of peak flow. But is it enough to be used in an equation and predict an accurate peak flow? The answer is yes. The equations that use watershed area as a predictor of peak flows have relatively high $R^2$ values (Equation 7, Equation 8). Area can be used to estimate the magnitude of a peak flow, but other predictors should be used when predicting interannual variation in peak discharges. Large watersheds, while influenced by meteorologist variables, are best estimated by the broader aspects of the watershed, such as area or slope. Figure 20 shows a linear equation that is accurate for larger watersheds, but returns negative peak flows estimates for watersheds smaller than 27 km$^2$. The figure suggests smaller watersheds have a non-linear relationship when estimating peak flows by area.

Why do all the watersheds have different significant independent variables that best predict peak flows? Roche Moutonnée Creek has a greater slope then the other three watersheds and is the farthest south. Putuligayuk River is the largest watershed as well as the lowest slope. Imnavait has the smallest area, but per normalized peak discharge, it has one of the highest rates of peak discharge to area.

SWE is a recurring significant independent variable (Table 7). Since all the peak flows selected for the study are snowmelt driven, this is an expected outcome. Snowmelt driven peak flows should have SWE as a significant predictor.

*Table 11 Final equations for peak discharge flows.*

| Watershed | Equation | $R^2$ |
|---|---|---|
| Upper Kuparuk River | $Q_p$=23.272SWE-13.352 | 0.54 ($p > 0.001$) |
| Putuligayuk River | $Q_p$=4.13$P_R$+0.684S+23.529 | 0.53 ($p = 0.070$) |
| Imnavait Creek | $Q_p$=0.053SWE+0.147 | 0.21 ($p = 0.014$) |
| All Watersheds I | $Q_p$=0.217A-5.678 | 0.72 ($p > 0.001$) |
| All Watersheds II | $Q_p$=2.170SWE+0.211A-27.005 | 0.68 ($p > 0.001$) |

The lowest $R^2$ value in Table 11 came from Imnavait Creek which was surprising considering how long data has been collected at that site. This signifies that there is some other predictor not accounted for that affects the peak flows more than the independent variables used in the equation. These predictors are likely related to antecedent storage conditions and rate of snowmelt. All Watersheds I had the highest $R^2$ value of the five linear regression equations. Followed by All Watersheds II and the Upper Kuparuk River equations. The p-value was significant as well.

The set of figures below show the estimated linear peak discharge equations for each watershed with historic peak flows. Figure 22 is the Upper Kuparuk Watershed simple linear regression. It has $R^2$ value of 0.54. The SWE value for 2015 was used to verify the equation, it was not included in creating the linear regression equation. The 2015 SWE data point is shown in green.

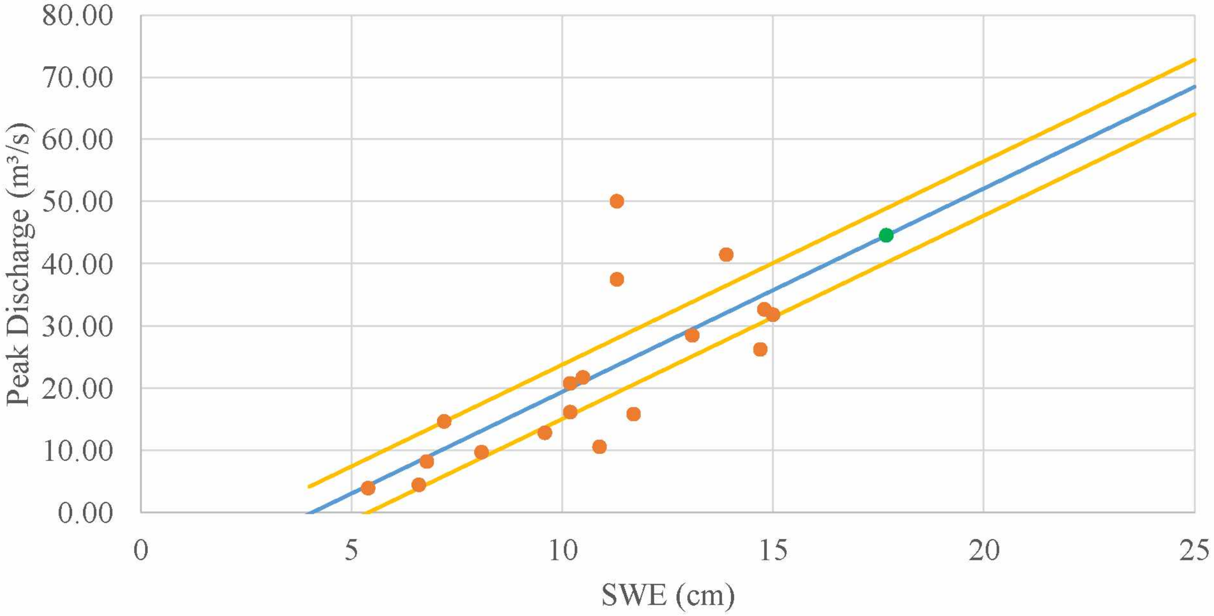

*Figure 22 Upper Kuparuk River linear regression equation with historic peak discharge points compared with Equation 4 and with 95% confidence intervals in yellow, the verifying 2015 data point is green.*

All of the peak flows used to estimate peak discharge were snowmelt driven. In three of the four cases where meteorological factors are used, SWE is the factor with the highest significance when estimating peak discharges.

Figure 23 shows the linear regression equation for the Putuligayuk River and historic peak flows. This equation used rainfall and storage to estimate peak discharge. The $R^2$ value is 0.53, the second lowest $R^2$ value in the data set, and the p-value is not significant ($p = 0.07$). The linear regression equation using one independent variable, storage, to estimate peak flows has a low $R^2$ value ($R^2 = 0.375$) and it is p-value is still not significant ($p = 0.060$). The effect of storage has shown to have strong controls on production of runoff in this watershed (Bowling et al. 2003; McNamara Kane et al. 1998; Bring et al. 2016; Stuefer et al. 2016). The rainfall and storage equation was picked as it had a high $R^2$ value.

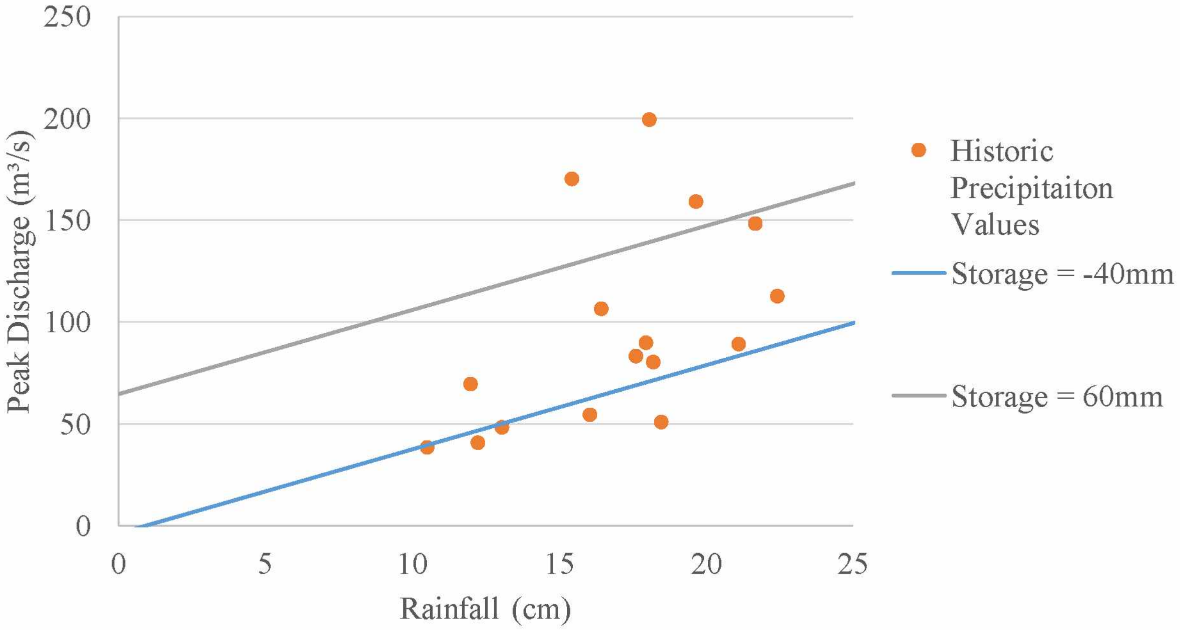

*Figure 23 Putuligayuk River linear regression equation with historic peak discharge points compared with Equation 9.*

Acknowledging the Putuligayuk River's low slope, and the significance of storage and rainfall variables means the last year's precipitation sits on the surface of the Putuligayuk Watershed and then settled into the storage zone as suggested by Bowling's paper on the role of surface storage in an arctic watershed (Bowling et al. 2003).

Figure 24 is a graph illustrating the linear regression equation for Imnavait Creek. Apart from 1 outlier, all the points are clustered in one area. That outlier is from 2013, it was an unusually high peak discharge (2.04 $m^3/s$) with, according to the equation, a low SWE (19.3 cm), however, it is largest SWE on record. With a low $R^2$ value of 0.21, this is not a good equation to use when estimating peak discharge in Imnavait Creek.

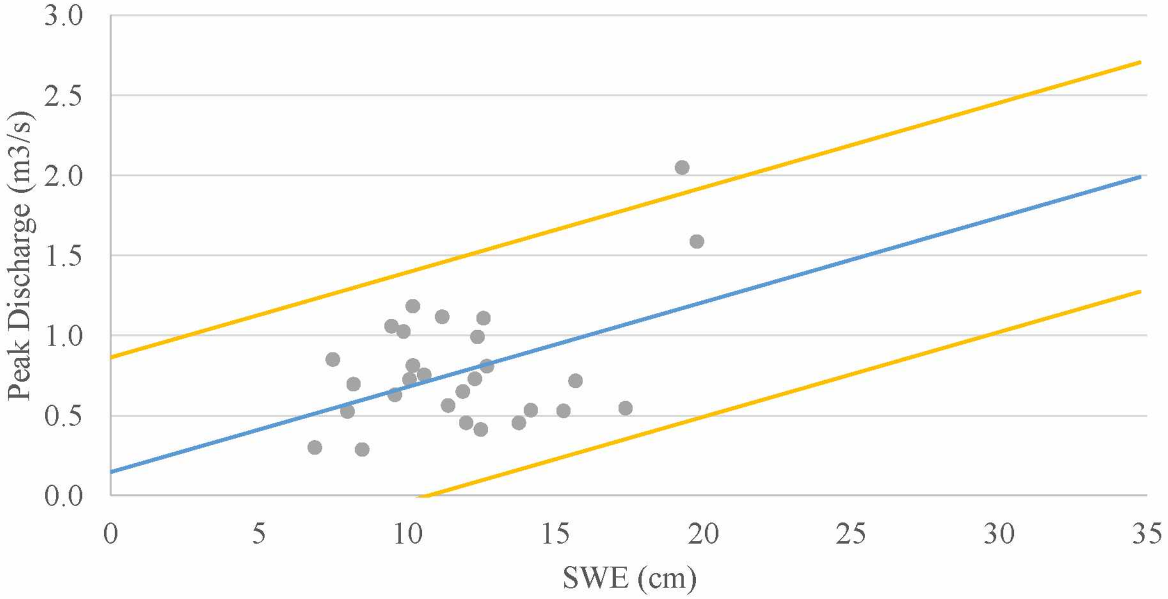

*Figure 24 Imnavait Creek linear regression equation with historic peak discharge points compared with Equation 6 and 95% confidence intervals.*

This equation has a low $R^2$ value, and all but two SWE measurements are clustered between 0.25 $m^3/s$ and 1.25 $m^3/s$ peak discharge. Considering how great the distance between the

95% confidence intervals, the linear regression equation created should not be used for estimating peak flows until more peak flow years are added and a better $R^2$ value is created.

# Chapter 7 Conclusions

In ungauged locations of the North Slope of Alaska, informed judgments on design flows must be made using data gathered from sites of similar climate and topography and by applying statistical or physically based models to the area. The North Slope of Alaska has potential for future development that would require judgments for building structures, road design, accurate hydrologic analysis of watersheds, monitoring watersheds and predicting erosion and sediment transport. Based on this study of four watersheds located on the northern side of the Brooks Range and on the Coastal Plain of North Slope, the following conclusions can be stated:

1. Area has the greatest influence on peak flows in any of the watersheds in this study. Area is such a large driver for peak flows, it overpowers any other independent variable included in a linear regression analyses.
2. For meteorological data, snow water equivalent and rainfall had a high correlation to peak flows.
3. Analysis of more arctic watersheds is needed to better understand landscape characteristics and to develop more accurate linear regression equations.
4. The best predictor of design peak flows of given annual exceedance probability (AEP) is historic peak flows.
5. The best equations for estimating peak discharges in ungauged watersheds uses the data from watersheds from similar areas. Once the watersheds start to lose common features, the equations become less accurate.

The difficulty with creating a model or equation to best predict peak flows is having a complete meteorological and hydrological dataset of a watershed in Alaska. The problem goes further than just a lack of historic data. Alaska is the largest state in the U.S. and yet, has less stream gauge stations per square mile than the rest of the continental US. There are current gaps in the hydrological and meteorological data collections (Kane and Stuefer 2015). Continuing long-term observations of discharge in Arctic watersheds will contribute to understanding the implication of climate change on the Arctic hydrologic system and the changing climatic drivers that affect peak discharges.

# Literature Cited

Arp, Christopher, and Svetlana L. Stuefer. 2016. "Hydrological and Meteorological Data from the North Slope of Alaska." University of Alaska Fairbanks, Water and Environmental Research Center. http://ine.uaf.edu/werc/teon.

Bailey, Meadow. 2016. "DOT: Dalton Highway Updates." *ADOT&PF*. http://dot.alaska.gov/nreg/dalton-updates/2015response.shtml.

Bowling, Laura C., Douglas L. Kane, Robert E. Gieck, Larry D. Hinzman, and Dennis P. Lettenmaier. 2003. "The Role of Surface Storage in a Low-Gradient Arctic Watershed." *Water Resources Research* 39 (4): n/a-n/a. doi:10.1029/2002WR001466.

Bring, A., I. Fedorova, Y. Dibike, L. Hinzman, J. Mård, S. H. Mernild, T. Prowse, O. Semenova, S. L. Stuefer, and M.-K. Woo. 2016. "Arctic Terrestrial Hydrology: A Synthesis of Processes, Regional Effects, and Research Challenges." *Journal of Geophysical Research: Biogeosciences* 121 (3): 621–49. doi:10.1002/2015JG003131.

Curran, Janet H., David F. Meyer, and Gary D. Tasker. 2003. "Estimating the Magnitude and Frequency of Peak Streamflows for Ungaged Sites on Streams in Alaska and Conterminous Basins in Canada." Vol. 1.10.

Curran, Janet H., Nancy A Barth, Andrea G Veilleux, and Robert T Ourso. 2016. "Estimating Flood Magnitude and Frequency at Gaged and Ungaged Sites on Streams in Alaska and Conterminous Basins in Canada, Based on Data through Water Year 2012." *Scientific Investigations Report*. Reston, VA. doi:10.3133/sir20165024.

Hamilton, Thomas D. 2003. "Glacial Geology of the Toolik Lake and Upper Kuparuk River Regions." *Biological Papers of the University of Alaska*, no. No. 26. https://scholarworks.alaska.edu/bitstream/handle/11122/1502/BiologicalPapers_no26.pdf?sequence=1.

Kane, Douglas L., and D. Yang. 2004. *Northern Research Basins Water Balance*. 20thed. IAHS Publication. Wallingford, UK: International Association of Hydrological Science.

Kane, Douglas L., Emily Youcha, Svetlana Stuefer, Greta Myerchin-Tape, Erica Lamb, Joel Homan, Robert Gieck, William Schnabel, and Horactio Toniolo. 2014. "Hydrology and Meteorology of the Central Alaska Arctic: Data Collection and Analysis." Fairbanks.

Kane, Douglas L., Emily Youcha, Svetlana Stuefer, Horacio Toniolo, William Schnabel, Robert E. Gieck, Greta Myerchin-Tape, Joel Homan, Erica Lamb, and Ken Tape. 2012. "Meteorological and Hydrological Data and Analysis Report for Foothills/Umiat Corridor and Bullen Projects: 2006-2011."

Kane, Douglas L., and Larry Hinzman. 2009. "Upper Kuparuk River, Imnavait Creek, Roche Moutonnee Creek, and Putuligayuk River Hydro-Meteorologic Datasets." Fairbanks: University of Alaska Fairbanks, Water and Environmental Research Center.

Kane, Douglas L., James P. McNamara, Daqing Yang, Peter Q. Olsson, and Robert E. Gieck. 2003. "An Extreme Rainfall/runoff Event in Arctic Alaska." *Journal of Hydrometeorology* 4 (6): 1220–28.

Kane, Douglas L., and Svetlana Stuefer. 2015. "Reflecting on the Status of Precipitation Data Collection in Alaska: A Case Study." *Hydrology Research* 46 (4): 478 LP-493. http://hr.iwaponline.com/content/46/4/478.abstract.

Knapp, Michael. 1995. "Alaska Highway Drainage Manual Chapter 7: Hydrology." http://www.dot.state.ak.us/stwddes/desbridge/assets/pdf/hwydrnman/ch7_0695.pdf.

McNamara, James P., Douglas L. Kane, and Larry D. Hinzman. 1997. "Hydrograph Separations in an Arctic Watershed Using Mixing Model and Graphical Techniques." *Water Resources Research* 33 (7): 1707–19. doi:10.1029/97WR01033.

McNamara, James P., Douglas L. Kane, and Larry D. Hinzman. 1998. "An Analysis of Streamflow Hydrology in the Kuparuk River Basin, Arctic Alaska: A Nested Watershed Approach." *Journal of Hydrology* 206 (1). Elsevier: 39–57. doi:10.1016/S0022-1694(98)00083-3.

McNamara, James P, Douglas L Kane, and Larry D Hinzman. 1999. "An Analysis of an Arctic Channel Network Using a Digital Elevation Model." *Geomorphology* 29 (3): 339–53. doi:10.1016/S0169-555X(99)00017-3.

Romanovsky, Vladimir E., Sharon L. Smith, and Hanne H. Christiansen. 2010. "Permafrost Thermal State in the Polar Northern Hemisphere during the International Polar Year 2007-2009: A Synthesis." *Permafrost and Periglacial Processes* 21 (2). John Wiley & Sons, Ltd.: 106–16. doi:10.1002/ppp.689.

Stuefer, Svetlana, Christopher D. Arp, Emily Youcha, J. Bradley, and Alexa Hinzman. 2016. "Terrestrial Environmental Observing Network (TEON) – the Kuparuk River." In *3rd Arctic Observing Summit, 2016, Fairbanks, Alaska*, Poster.

Stuefer, Svetlana, Douglas L. Kane, and Robert Gieck. 2016. "Snowmelt Water Balance for a Permafrost Watershed: Case Study from Alaska Arctic." In *XI. International Conference on Permafrost*, edited by H. Hubberten, 686–686. Potsdam: Alfred Wegener Institute.

Stuefer, Svetlana, Douglas L. Kane, and Glen E. Liston. 2013. "In Situ Snow Water Equivalent Observations in the US Arctic." *Hydrology Research* 44 (1). IWA Publishing: 21–34.

U.S. Interagency Advisory Committee on Water Data. 1982. "Guidelines for Determining Flood Flow Frequency, Bulletin 17B of the Hydrology Subcommittee." Edited by U.S. Geological Survey. Reston, Virginia: Office of Water Data Coordination.

———. 2016. “Guidelines for Determingin Flood Flow Frequency, Bulletin 17C of the Hydrology Subcommittee - Draft.” Reston, Virginia.

USACE. 2015. “Chena River Lakes Flood Control Project And Tanana River Levee.” Fairbanks.
Weisberg, Sanford. 2014. *Applied Linear Regression*. 4th ed. Minneapolis, MN: John Wiley & Sons, Inc.

Wurbs, Ralph A., and Wesley P. James. 2002. *Water Resources Engineering*. Upper Saddle River, NJ: Prentice Hall.

Yoshikawa, Kenji, Larry D. Hinzman, and Douglas L. Kane. 2007. “Spring and Aufeis (Icing) Hydrology in Brooks Range, Alaska.” *Journal of Geophysical Research: Biogeosciences* 112 (G4): n/a-n/a. doi:10.1029/2006JG000294.

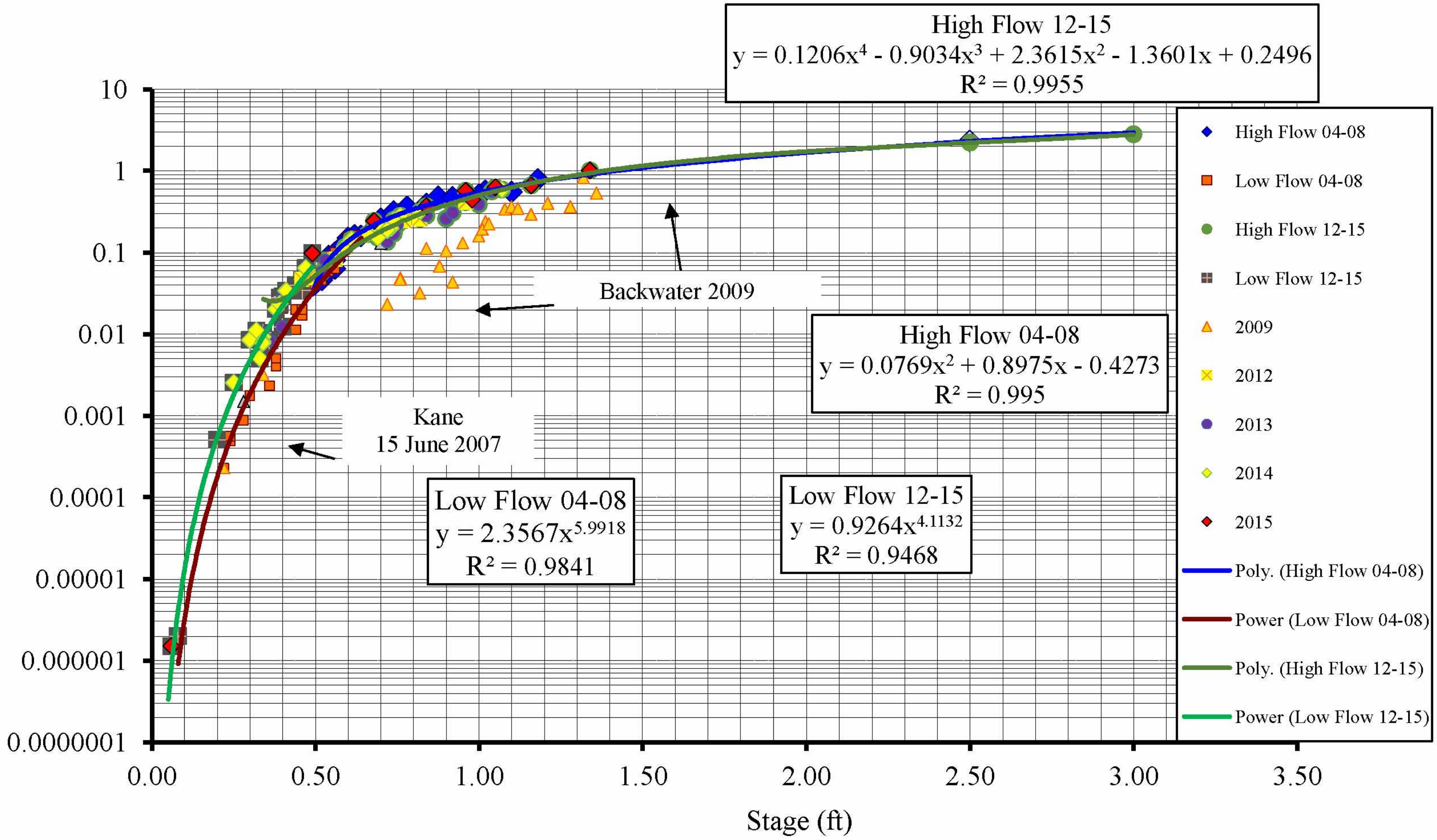

*Figure 25 Stage-Discharge Relation for Imnavait Creek Weir 2004-2008 and 2012-2015 (Kane and Hinzman 2009; Arp and Stuefer 2016).*

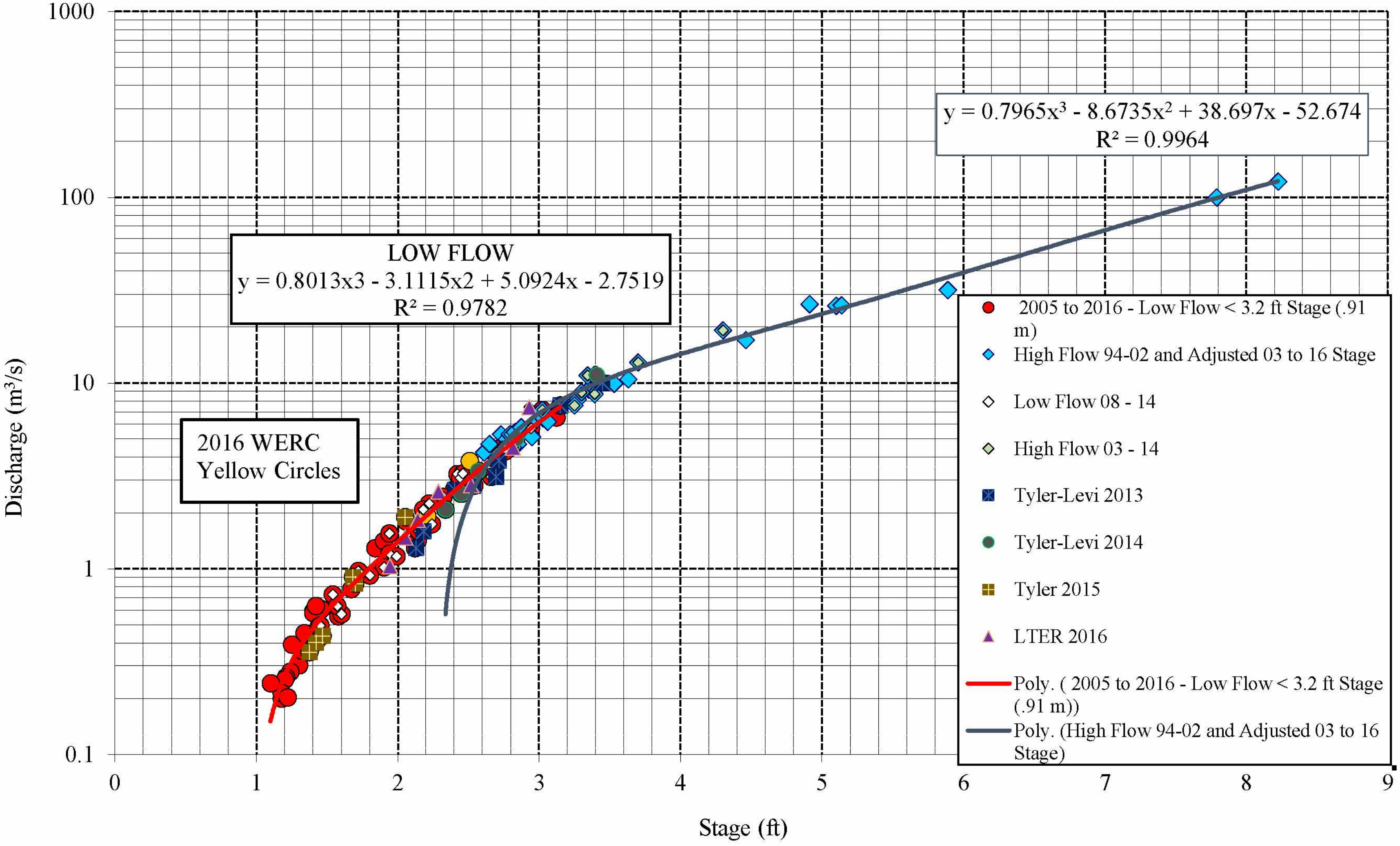

*Figure 26 Upper Kuparuk River 1994-2002 Rating Curves Adjusted High Flow and Upper Kuparuk River 2005 to 2016 New Rating Curve To convert Tylers 2014 BM to old staff gauge add 0.73 ft. Stage-Discharge Relation for Upper Kuparuk Rive. (Kane and Hinzman 2009; Arp and Stuefer 2016)*

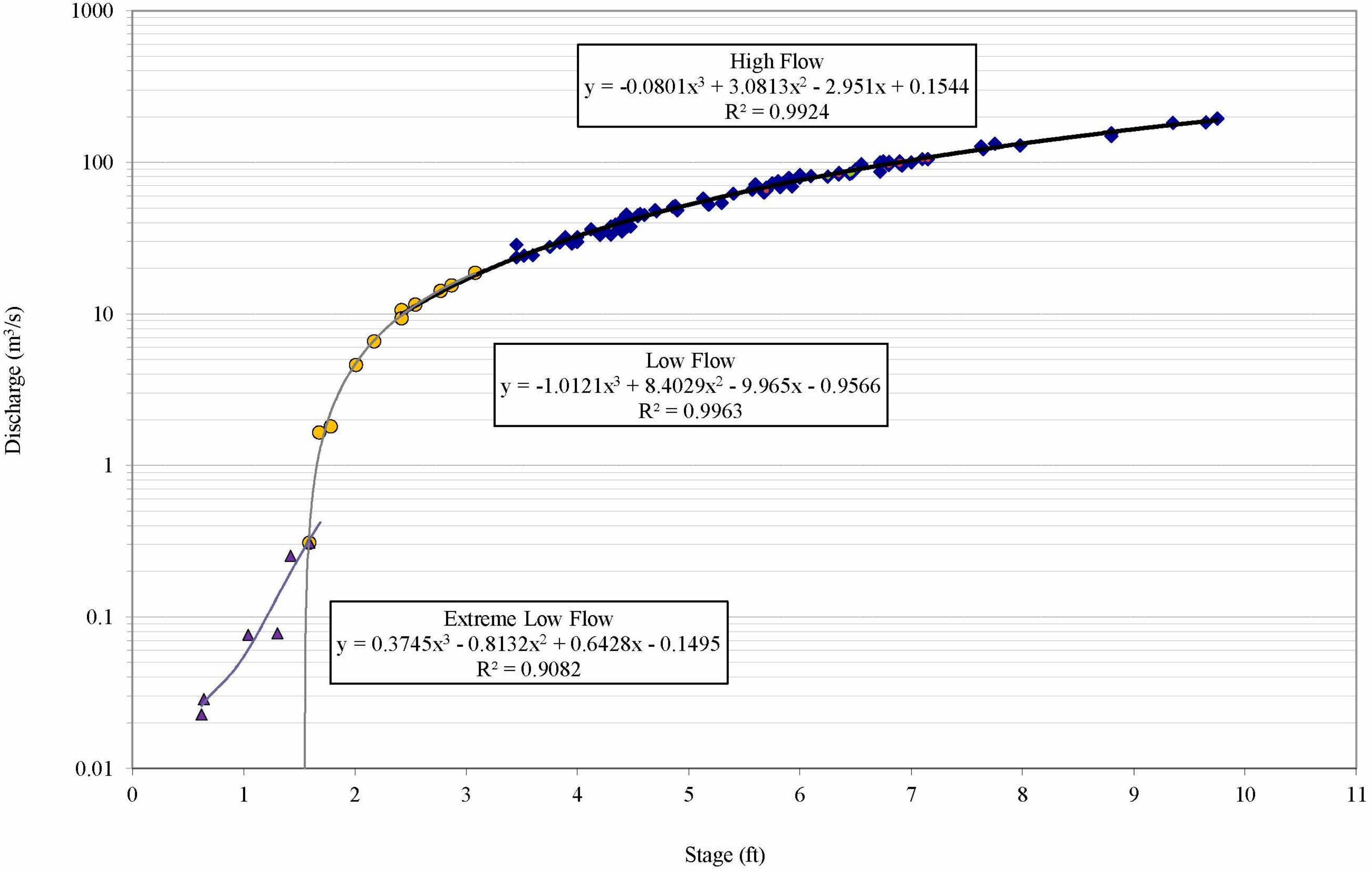

*Figure 27 Stage-Discharge Relation for Putuligayuk River at Spine Road High Flow 1974 - 2015 (Kane and Hinzman 2009; Arp and Stuefer 2016).*

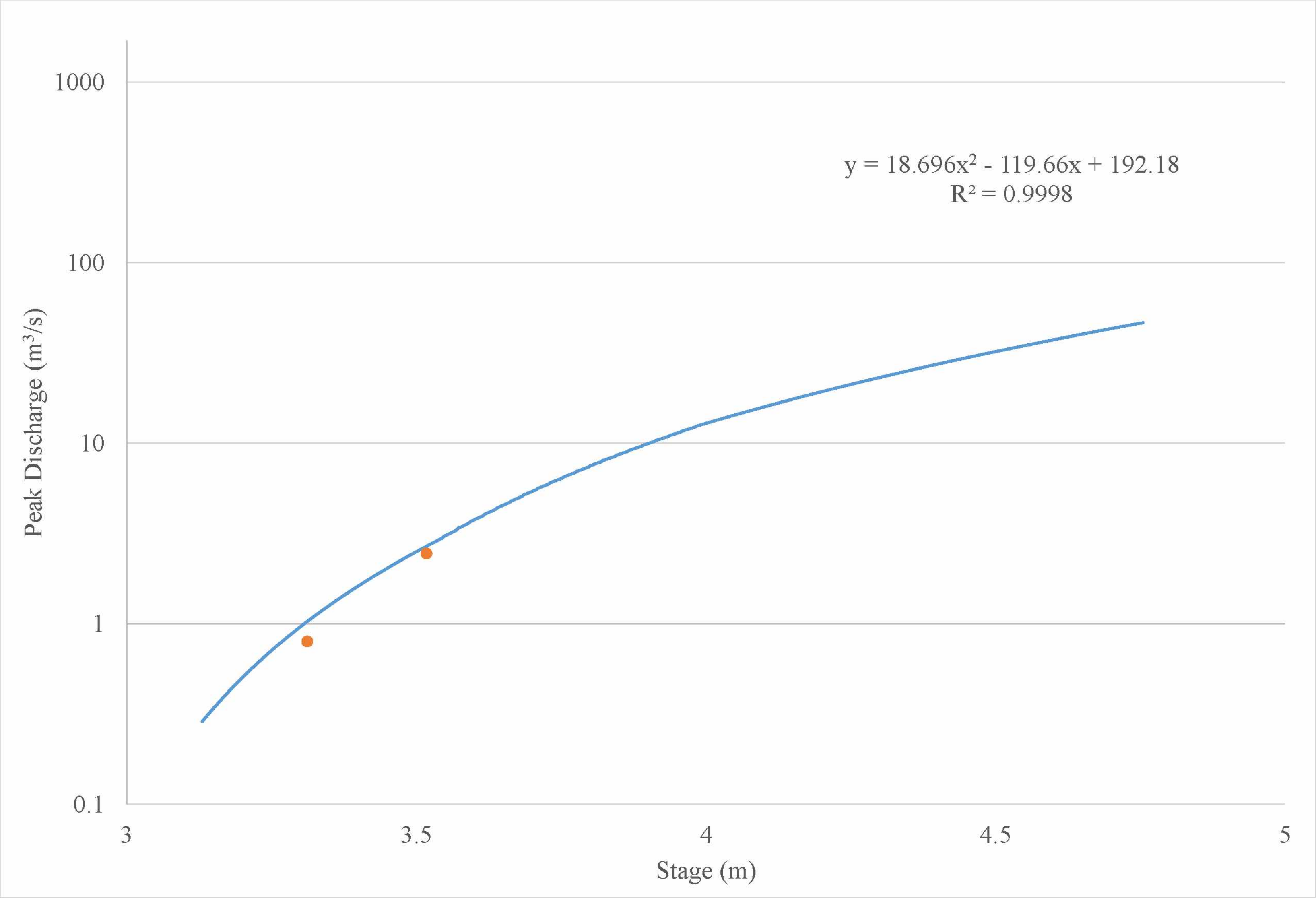

*Figure 28 Stage-Discharge Relation for Roche Moutonnée Creek (U.S. Geological Survey 2016) The points are from TEON's new Roche Moutonnée gauging station.*

*Table 12 Summary of hydrological and meteorological data for the Putuligayuk River Watershed.*

| Year | Peak Month | Peak Day | Julian | Time | Peak Discharge | Normalized $Q_p$ | SWE | Storage | Previous Year's Rainfall |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | $m^3/s$ | $m^3/(s*km^2)$ | cm | mm | cm |
| 1999 | 6.00 | 10 | 161 | 18:00 | 48.090 | 0.102 | 10.4 | | 13.07 |
| 2000 | 6.00 | 16 | 168 | 5:00 | 159.140 | 0.338 | 11.5 | 56 | 19.66 |
| 2001 | 6.00 | 12 | 163 | 17:00 | 50.782 | 0.108 | 10.9 | -34 | 18.49 |
| 2002 | 5.00 | 26 | 146 | 9:30 | 54.497 | 0.116 | 10.9 | 5 | 16.07 |
| 2003 | 6.00 | 7 | 158 | 8:15 | 138.798 | 0.295 | 12 | 11 | 28.96 |
| 2004 | 6.00 | 7 | 159 | 4:00 | 170.200 | 0.361 | 10.4 | -11 | 15.44 |
| 2005 | 6.00 | 10 | 161 | 2:30 | 80.187 | 0.170 | 10.8 | -41 | 18.21 |
| 2006 | 6.00 | 3 | 154 | 6:30 | 40.549 | 0.086 | 10 | -21 | 12.25 |
| 2007 | 6.00 | 7 | 158 | 8:30 | 69.447 | 0.147 | 10.4 | 29 | 12 |
| 2008 | 6.00 | 1 | 153 | 21:45 | 38.276 | 0.081 | 9.2 | -41 | 10.52 |
| 2009 | 6.00 | 5 | 156 | 4:00 | 148.400 | 0.315 | 14.1 | 46 | 21.7 |
| 2010 | 6.00 | 8 | 159 | 3:45 | 199.386 | 0.423 | 10.5 | | 18.09 |
| 2011 | 6.00 | 6 | 158 | 8:30 | 83.070 | 0.176 | 14.8 | | 17.62 |
| 2012 | 6.00 | 8 | 159 | 12:00 | 89.760 | 0.191 | 13.9 | | 17.97 |
| 2013 | 6.00 | 10 | 161 | 6:00 | 106.338 | 0.226 | 9.3 | | 16.45 |
| 2014 | 6.00 | 4 | 155 | 22:40 | 89.218 | 0.189 | | | 21.13 |
| 2015 | 5.00 | 24 | 144 | 13:45 | 112.532 | 0.239 | | | 22.43 |

(Kane and Hinzman 2009; Arp and Stuefer 2016)

*Table 13 Summary of hydrological and meteorological data for the Upper Kuparuk River Watershed.*

| Year | Peak Month | Peak Day | Peak Time | Julian Day | Peak Discharge | Normalized $Q_p$ | SWE | Precipitation | Length of melt | Rainfall |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $m^3/s$ | $m^3/(s*km^2)$ | cm | cm | Days | cm |
| 1993 | 5 | 20 | 20:15 | 140 | 13.85 | 0.10 | | | | |
| 1994 | 5 | 19 | 19:25 | 139 | 22.16 | 0.16 | | | | 28.28 |
| 1995 | 5 | 13 | 21:10 | 133 | 24.72 | 0.17 | | | | 29.85 |
| 1996 | 5 | 29 | 19:55 | 150 | 26.16 | 0.18 | *14.7* | *38.9* | | *24.2* |
| 1997 | 6 | 5 | 19:55 | 156 | 31.69 | 0.22 | *15* | *46* | | *31* |
| 1998 | 5 | 35 | 16:05 | 145 | 9.64 | 0.07 | *8.1* | *31.7* | | *23.6* |
| 1999 | 5 | 23 | 20:00 | 144 | 3.84 | 0.15 | *5.4* | *37.8* | 6 | *32.4* |
| 2000 | 6 | 6 | 19:55 | 158 | 32.57 | 0.23 | *14.8* | *35.3* | 6 | *20.5* |
| 2001 | 6 | 3 | 19:30 | 154 | 15.78 | 0.11 | *11.7* | *33.9* | 7 | *22.2* |
| 2002 | 5 | 24 | 19:30 | 144 | 21.62 | 0.15 | *10.5* | *39.9* | 12 | *29.4* |
| 2003 | 6 | 6 | 20:45 | 157 | 41.34 | 0.29 | 13.9 | 28.97 | 16 | 15.07 |
| 2004 | 5 | 24 | 21:45 | 145 | 20.65 | 0.15 | 10.2 | | 11 | |
| 2005 | 5 | 14 | 19:30 | 134 | 10.45 | 0.07 | 10.9 | 26.17 | 8 | 15.27 |
| 2006 | 5 | 20 | 20:30 | 140 | 8.09 | 0.06 | 6.8 | 27.07 | 9 | 20.27 |
| 2007 | 5 | 27 | 7:15 | 147 | 16.10 | 0.11 | 10.2 | 20.2 | 12 | 10 |
| 2008 | 5 | 23 | 21:30 | 145 | 4.40 | 0.03 | 6.6 | 30.28 | 11 | 23.68 |
| 2009 | 5 | 24 | 20:15 | 144 | 28.38 | 0.20 | 13.1 | 37.37 | | 24.27 |
| 2010 | 5 | 23 | 22:00 | 143 | 14.59 | 0.10 | 7.2 | 34.74 | | 27.54 |
| 2011 | 5 | 23 | 20:00 | 143 | 50.00 | 0.35 | 11.3 | 22.95 | 11 | 11.65 |
| 2012 | 5 | 24 | 21:00 | 145 | 12.77 | 0.09 | 9.6 | 33.21 | 11 | 23.61 |
| 2013 | 6 | 3 | 18:00 | 154 | 37.43 | 0.26 | 11.3 | 37.82 | | 26.52 |
| 2014 | 5 | 30 | 20:45 | 150 | 40.59 | 0.29 | | | | |
| 2015 | 5 | 18 | 20:30 | 138 | 44.55 | 0.314 | | | | |

*Italicized numbers indicate published data in the article "Hydrological cycle on the North Slope of Alaska" in the book Northern Research Basins Water Balance (Kane and Yang 2004).* (Kane and Hinzman 2009; Arp and Stuefer 2016)

*Table 14 Summary of hydrological and meteorological data for the Imnavait Creek Watershed.*

| Year | Peak Month | Peak Day | Peak Time | Peak Q | Normalized Peak Q | Julian Day | Precipitation | Storage | Rainfall | SWE total | Length of melt |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Month | Day | Hour | m³/s | m³/(s*km²) | | cm | mm | cm | cm | days |
| 1985 | 5 | 25 | 16:00 | 0.750 | 0.341 | 145 | *25.1* | | 19.7 | 10.6 | 13 |
| 1986 | 6 | 5 | 15:04 | 0.559 | 0.254 | 156 | *16.3* | -18 | 19.1 | 11.4 | 9 |
| 1987 | 5 | 22 | 17:02 | 0.807 | 0.367 | 142 | *27.2* | -37 | 17.8 | 10.2 | 9 |
| 1988 | 5 | 14 | 16:00 | 0.846 | 0.385 | 135 | *25.2* | 18 | 21.3 | 7.5 | 6 |
| 1989 | 5 | 30 | 18:00 | 1.104 | 0.502 | 150 | *25.7* | 69 | 26.4 | 12.6 | 13 |
| 1990 | 5 | 17 | 8:09 | 1.020 | 0.464 | 137 | *16.3* | 30 | 10.2 | 9.9 | 10 |
| 1991 | 5 | 8 | 18:57 | 0.690 | 0.314 | 128 | *24.9* | 24 | 10.3 | 8.2 | 6 |
| 1992 | 6 | 6 | 0:00 | 0.523 | 0.238 | 154 | *24.1* | 61 | 11.7 | 15.3 | 14 |
| 1993 | 5 | 18 | 16:36 | 0.720 | 0.327 | 138 | *20.8* | -1 | 20.3 | 10.1 | 8 |
| 1994 | 5 | 17 | 16:32 | 0.520 | 0.236 | 137 | *27.1* | -10 | 24.9 | 8.0 | 10 |
| 1995 | 5 | 11 | 15:41 | 0.530 | 0.241 | 131 | *20.9* | -36 | 21.3 | 14.2 | 10 |
| 1996 | 5 | 25 | 18:00 | 1.178 | 0.535 | 146 | *18.8* | -5 | 15.0 | 10.2 | 10 |
| 1997 | 5 | 27 | 22:00 | 0.407 | 0.185 | 147 | *25.5* | 12 | 30.7 | 12.5 | 16 |
| 1998 | 6 | 3 | 13:50 | 1.054 | 0.479 | 154 | *23.8* | -50 | 24.8 | 9.5 | 8 |
| 1999 | 5 | 17 | 17:15 | 0.295 | 0.134 | 139 | *34.2* | -6 | 34.3 | 6.9 | 11 |
| 2000 | 6 | 4 | 16:45 | 1.114 | 0.506 | 156 | *23.2* | -19 | 23.1 | 11.2 | 11 |
| 2001 | 6 | 2 | 10:30 | 0.802 | 0.365 | 153 | *20.4* | 5 | 20.4 | 12.7 | 12 |
| 2002 | 5 | 22 | 16:45 | 0.987 | 0.449 | 143 | *30.3* | -30 | 30.0 | 12.4 | 9 |
| 2003 | 6 | 3 | 11:15 | 0.713 | 0.324 | 154 | *28.4* | 3 | 31.2 | 15.7 | 10 |
| 2004 | 5 | 23 | 18:00 | 0.448 | 0.204 | 144 | 22.6 | | 20.8 | 12.0 | 10 |
| 2005 | 5 | 13 | 13:30 | 0.647 | 0.294 | 133 | 5.6 | | 11.7 | 11.9 | 11 |
| 2006 | 5 | 19 | 16:45 | 0.627 | 0.285 | 139 | | | 25.1 | 9.6 | 10 |
| 2007 | 5 | 25 | 18:30 | 0.725 | 0.329 | 145 | 7.2 | | 25.8 | 12.3 | 13 |
| 2008 | 5 | 28 | 0:30 | 0.285 | 0.130 | 149 | 18.8 | | 23.1 | 8.5 | 11 |
| 2009 | 5 | 24 | 20:45 | 0.542 | 0.246 | 144 | 36.0 | | 25.4 | 17.4 | 13 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2010 | | | | | | | 24.3 | | 22.1 | | |
| 2011 | | | | | | | 12.8 | | 13.0 | | |
| 2012 | 5 | 24 | 20:00 | 0.452 | 0.205 | 145 | 26.6 | | 26.7 | 13.8 | 17 |
| 2013 | 5 | 29 | 13:45 | 2.044 | 0.929 | 149 | 25.8 | | 25.9 | 19.3 | 16 |
| 2014 | 5 | 30 | 17:15 | 1.165 | 0.529 | 150 | | | | | |
| 2015 | 5 | 15 | 8:30 | 1.584 | 0.720 | 136 | 6.8 | | | 19.8 | 15 |

(Kane and Hinzman 2009; Arp and Stuefer 2016)

*Table 15 Summary of hydrological and meteorological data for Roche Moutonnée Creek Watershed.*

| Year | Peak Month | Peak Day | Time | Peak Discharge | Julian Day |
|---|---|---|---|---|---|
| | Month | Day | | $m^3/s$ | |
| 1976 | 6 | 29 | | 28.317 | 181 |
| 1977 | 6 | 9 | | 7.108 | 160 |
| 1978 | 6 | 5 | | 2.008 | 156 |
| 1979 | 6 | 28 | | 1.676 | 179 |
| 1980 | 6 | 4 | | 0.858 | 156 |
| 1981 | 6 | 17 | | 4.786 | 168 |
| 1982 | 6 | 16 | | 1.291 | 168 |
| 1984 | 6 | 16 | | 7.249 | 167 |
| 1985 | 6 | 27 | 11:20 | 5.154 | 178 |
| 1986 | 6 | 13 | 13:10 | 1.943 | 165 |
| 1990 | 6 | 28 | 1:25 | 11.242 | 179 |
| 1991 | 6 | 8 | 12:10 | 2.735 | 159 |
| 1994 | 5 | 25 | 21:35 | 1.220 | 145 |
| 1998 | 5 | 30 | 22:49 | 5.947 | 150 |
| 2001 | 6 | 8 | 1:17 | 5.975 | 159 |
| 2002 | 5 | 24 | 19:15 | 5.437 | 144 |
| 2003 | 6 | 4 | 16:09 | 1.937 | 155 |
| 2005 | 6 | 4 | 15:53 | 1.308 | 155 |
| 2009 | 6 | 25 | 14:11 | 5.663 | 176 |
| 2011 | 6 | 3 | 17:21 | 1.218 | 154 |
| 2012 | 6 | 5 | 16:17 | 5.040 | 157 |
| 2013 | 6 | 4 | 13:16 | 2.727 | 155 |
| 2014 | 5 | 30 | 18:52 | 5.522 | 150 |
| 2015 | 5 | 28 | 19:47 | 7.646 | 148 |
| 2016 | 5 | 30 | 20:47 | 1.583 | 151 |

(Kane and Hinzman 2009; Arp and Stuefer 2016)

*Table 16 Summary of physiographic, hydrological and meteorological data for all watersheds.*

| Year | Peak Discharge | Normalized Peak Discharge | SWE | Area | Storage | Slope |
|---|---|---|---|---|---|---|
| | m³/s | m³/(s*km²) | cm | km² | mm | (km/km) |
| Imnavait Creek | | | | | | |
| 1985 | 0.750 | 0.341 | 10.61 | 2.2 | | 0.027 |
| 1986 | 0.559 | 0.254 | 11.43 | 2.2 | | 0.027 |
| 1987 | 0.807 | 0.367 | 10.2 | 2.2 | -18 | 0.027 |
| 1988 | 0.846 | 0.385 | 7.5 | 2.2 | -37 | 0.027 |
| 1989 | 1.104 | 0.502 | 12.6 | 2.2 | 18 | 0.027 |
| 1990 | 1.020 | 0.464 | 9.91 | 2.2 | 69 | 0.027 |
| 1991 | 0.690 | 0.314 | 8.16 | 2.2 | 30 | 0.027 |
| 1992 | 0.523 | 0.238 | 15.28 | 2.2 | 24 | 0.027 |
| 1993 | 0.720 | 0.327 | 10.13 | 2.2 | 61 | 0.027 |
| 1994 | 0.520 | 0.236 | 8.02 | 2.2 | -1 | 0.027 |
| 1995 | 0.530 | 0.241 | 14.2 | 2.2 | -10 | 0.027 |
| 1996 | 1.178 | 0.535 | 10.2 | 2.2 | -36 | 0.027 |
| 1997 | 0.407 | 0.185 | 12.5 | 2.2 | -5 | 0.027 |
| 1998 | 1.054 | 0.479 | 9.5 | 2.2 | 12 | 0.027 |
| 1999 | 0.295 | 0.134 | 6.9 | 2.2 | -50 | 0.027 |
| 2000 | 1.114 | 0.506 | 11.2 | 2.2 | -6 | 0.027 |
| 2001 | 0.802 | 0.365 | 12.7 | 2.2 | -19 | 0.027 |
| 2002 | 0.987 | 0.449 | 12.37 | 2.2 | 5 | 0.027 |
| 2003 | 0.713 | 0.324 | 15.66 | 2.2 | -30 | 0.027 |
| 2004 | 0.448 | 0.204 | 12.04 | 2.2 | 3 | 0.027 |
| 2005 | 0.647 | 0.294 | 11.9 | 2.2 | | 0.027 |
| 2006 | 0.627 | 0.285 | 9.6 | 2.2 | | 0.027 |
| 2007 | 0.725 | 0.329 | 12.3 | 2.2 | | 0.027 |
| 2008 | 0.285 | 0.130 | 8.5 | 2.2 | | 0.027 |
| 2009 | 0.542 | 0.246 | 17.4 | 2.2 | | 0.027 |
| 2012 | 0.452 | 0.205 | 13.9 | 2.2 | | 0.027 |
| 2013 | 2.044 | 0.929 | 19.3 | 2.2 | | 0.027 |
| 2014 | 1.165 | 0.529 | | 2.2 | | 0.027 |
| 2015 | 1.584 | 0.720 | | 2.2 | | 0.027 |
| Putuligayuk River | | | | | | |
| 1999 | 48.090 | 0.102 | 10.4 | 471 | 56 | 0.0015 |
| 2000 | 159.140 | 0.338 | 11.5 | 471 | -34 | 0.0015 |
| 2001 | 50.782 | 0.108 | 10.9 | 471 | 5 | 0.0015 |
| 2002 | 54.497 | 0.116 | 10.9 | 471 | 11 | 0.0015 |
| 2003 | 138.798 | 0.295 | 12 | 471 | -11 | 0.0015 |
| 2004 | 170.200 | 0.361 | 10.4 | 471 | -41 | 0.0015 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 2005 | 80.187 | 0.170 | 10.8 | 471 | -21 | 0.0015 |
| 2006 | 40.549 | 0.086 | 10 | 471 | 29 | 0.0015 |
| 2007 | 69.447 | 0.147 | 10.4 | 471 | -41 | 0.0015 |
| 2008 | 38.276 | 0.081 | 9.2 | 471 | 46 | 0.0015 |
| 2009 | 148.400 | 0.315 | 14.1 | 471 | | 0.0015 |
| 2010 | 199.386 | 0.423 | 10.5 | 471 | | 0.0015 |
| 2011 | 83.070 | 0.176 | 14.8 | 471 | | 0.0015 |
| 2012 | 89.760 | 0.191 | | 471 | | 0.0015 |
| 2013 | 106.338 | 0.226 | | 471 | | 0.0015 |
| 2014 | 89.218 | 0.189 | | 471 | | 0.0015 |
| 2015 | 112.532 | 0.239 | | 471 | | 0.0015 |
| Upper Kuparuk River | | | | | | |
| 1993 | 13.85 | 0.098 | | 142 | | 0.04475 |
| 1994 | 22.16 | 0.156 | | 142 | | 0.04475 |
| 1995 | 24.72 | 0.174 | | 142 | | 0.04475 |
| 1996 | 26.16 | 0.184 | 14.7 | 142 | | 0.04475 |
| 1997 | 31.69 | 0.223 | 15 | 142 | | 0.04475 |
| 1998 | 9.64 | 0.068 | 8.1 | 142 | | 0.04475 |
| 1999 | 3.84 | 0.027 | 5.4 | 142 | | 0.04475 |
| 2000 | 32.57 | 0.229 | 14.8 | 142 | | 0.04475 |
| 2001 | 15.78 | 0.111 | 11.7 | 142 | | 0.04475 |
| 2002 | 21.619 | 0.152 | 10.5 | 142 | | 0.04475 |
| 2003 | 41.344 | 0.291 | 13.9 | 142 | | 0.04475 |
| 2004 | 20.65 | 0.145 | 10.2 | 142 | | 0.04475 |
| 2005 | 10.45388 | 0.074 | 10.9 | 142 | | 0.04475 |
| 2006 | 8.094 | 0.057 | 6.8 | 142 | | 0.04475 |
| 2007 | 16.101 | 0.113 | 10.2 | 142 | | 0.04475 |
| 2008 | 4.398 | 0.031 | 6.6 | 142 | | 0.04475 |
| 2009 | 28.38 | 0.200 | 13.1 | 142 | | 0.04475 |
| 2010 | 14.59 | 0.103 | 7.2 | 142 | | 0.04475 |
| 2011 | 50 | 0.352 | 11.3 | 142 | | 0.04475 |
| 2012 | 12.77 | 0.090 | 9.6 | 142 | | 0.04475 |
| 2013 | 37.43 | 0.264 | 11.3 | 142 | | 0.04475 |
| 2014 | 40.586 | 0.286 | | 142 | | 0.04475 |
| 2015 | 44.55 | 0.314 | 17.7 | 142 | | 0.04475 |
| Roche Moutonnée Creek | | | | | | |
| 1976 | 28.317 | 0.337 | | 84 | | 0.164 |
| 1977 | 7.108 | 0.085 | | 84 | | 0.164 |
| 1978 | 2.008 | 0.024 | | 84 | | 0.164 |
| 1979 | 1.676 | 0.020 | | 84 | | 0.164 |
| 1980 | 0.858 | 0.010 | | 84 | | 0.164 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1981 | 4.786 | 0.057 | | 84 | | 0.164 |
| 1982 | 1.291 | 0.015 | | 84 | | 0.164 |
| 1984 | 7.249 | 0.086 | | 84 | | 0.164 |
| 1985 | 5.154 | 0.061 | | 84 | | 0.164 |
| 1986 | 1.943 | 0.023 | | 84 | | 0.164 |
| 1990 | 11.242 | 0.134 | | 84 | | 0.164 |
| 1991 | 2.735 | 0.033 | | 84 | | 0.164 |
| 1994 | 1.220 | 0.015 | | 84 | | 0.164 |
| 1998 | 5.947 | 0.071 | | 84 | | 0.164 |
| 2001 | 5.975 | 0.071 | | 84 | | 0.164 |
| 2002 | 5.437 | 0.065 | | 84 | | 0.164 |
| 2003 | 1.937 | 0.023 | | 84 | | 0.164 |
| 2005 | 1.308 | 0.016 | | 84 | | 0.164 |
| 2009 | 5.663 | 0.067 | | 84 | | 0.164 |
| 2011 | 1.218 | 0.014 | | 84 | | 0.164 |
| 2012 | 5.040 | 0.060 | | 84 | | 0.164 |
| 2013 | 2.727 | 0.032 | | 84 | | 0.164 |
| 2014 | 5.522 | 0.066 | | 84 | | 0.164 |
| 2015 | 7.646 | 0.091 | | 84 | | 0.164 |
| 2016 | 1.583 | 0.019 | | 84 | | 0.164 |

(Kane and Hinzman 2009; Arp and Stuefer 2016)