

*Estimates of Glacier Mass Loss and Contribution to Streamflow:
Wind River Range (Wyoming, USA)*

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ABSTRACT

The Wind River Range is a continuous mountain range approximately 160 km in length in west-central Wyoming. The Wind River Range is host to roughly 680 snow and ice bodies with 63 of these considered glaciers including seven of the ten largest glaciers in the American Rocky Mountains. The presence of glaciers results in meltwater contributions to streamflow during the late summer (July, August, and September – JAS) when snowmelt is decreasing, temperatures are high, precipitation is low, and irrigation demand continues. Most studies indicate that the glaciers in the Wind River Range have been retreating since the 1850's, the approximate end of the Little Ice Age. Thus, the quantification of glacier meltwater (e.g., volume, mass) contributions to late-summer/early-fall streamflow is important given this resource is dwindling due to glacier recession.

The current research expands upon previous research efforts and identified two glaciated watersheds, one on the east slope (Bull Lake Creek) and one on the west slope (Green River) of the Wind River Range in which unimpaired streamflow is available from 1966 to 2006. Glaciers were delineated within each watershed and area estimates (with error) were obtained for the years 1966, 1989 and 2006. Glacier volume (mass) loss (with error) was estimated using empirically based volume-area scaling relationships. For 1966 to 2006, glacier mass contributions to JAS streamflow on the east slope were approximately 8% while on the west slope were approximately 2%. The volume-area scaling glacier mass estimates compared favorably with measured (stereo-pairs remote sensed data) estimates of glacier mass change for three glaciers (Teton, Middle Teton, Teepee) in the nearby Teton Range and one glacier (Dinwoody) in the Wind River Range. While glacier mass contribution to JAS streamflow was estimated at 8% (east slope) and 2% (west slope) from 1966 to 2006, an increase was observed

during the period of 1989 to 2006 ($>11\%$ - east slope and $>3\%$ - west slope). Historic climate data, including precipitation (snowpack) and temperature (JAS average) showed a decrease in snowpack and rapid increase in temperatures during the 1989 to 2006 period, which most likely explains this increase in glacier melt.

TABLE OF CONTENTS

Introduction.....	1
Data.....	4
Streamflow from Glaciated Watersheds.....	4
Glacier Area.....	6
Methods and Results.....	11
Methods.....	11
Results.....	12
Discussion and Conclusions.....	15
References Cited.....	19
Appendices.....	24
Appendix A.....	25
Appendix B.....	28
Appendix C.....	33
Appendix D.....	35
VITA.....	41

INTRODUCTION

The Wind River Range is a continuous mountain range approximately 160 km in length in west-central Wyoming (Figure 1). The barrier (continental divide) serves as the dividing entity for three major river basins: Wind-Bighorn/Missouri/Mississippi, Green/Colorado, and the Snake/Columbia (Marston et al., 1991). The Wind River Range is host to roughly 680 snow and ice bodies with 63 of these considered glaciers including seven of the ten largest glaciers in the American Rocky Mountains (Bonney, 1987). The east slope of the divide contains roughly 77% of the total glacier area while the west slope contains the remaining area (Marston et al., 1991). Glaciers serve as valuable frozen, fresh water reservoirs, storing water in the winter and releasing it during the warmer summer months (Marston, 1989). The presence of glaciers results in meltwater contributions to streamflow during the late summer months (July, August and September – JAS) when snowmelt is decreasing, temperatures are still high, precipitation is generally low, and irrigation demand continues (Fountain and Tangborn 1985; Pochop et al., 1990). Thus, watersheds with glaciers are shown to provide a more stable source of water than non-glaciated watersheds (Ferguson, 1973; Fountain and Tangborn, 1985; Braithwaite and Olsen, 1988). Glaciers also affect the annual hydrograph by delaying seasonal runoff through internal storage of liquid water, resulting from snow melt, for release later in the year. The melt water from these glaciers is thought to be important during the warmer summer and fall months to supplement flows needed for irrigation, fisheries and the fulfillment of interstate water compacts. Most studies (e.g., Dyson, 1952; Mears, 1972; Meier, 1951) indicate that the glaciers in the Wind River Range have been retreating since the 1850's, the approximate end of the Little Ice Age (Marston et. al., 1991). Thus, the quantification of glacier meltwater (e.g., volume,

mass) contributions to late-summer/early-fall streamflow is important given this resource is dwindling due to glacier recession.

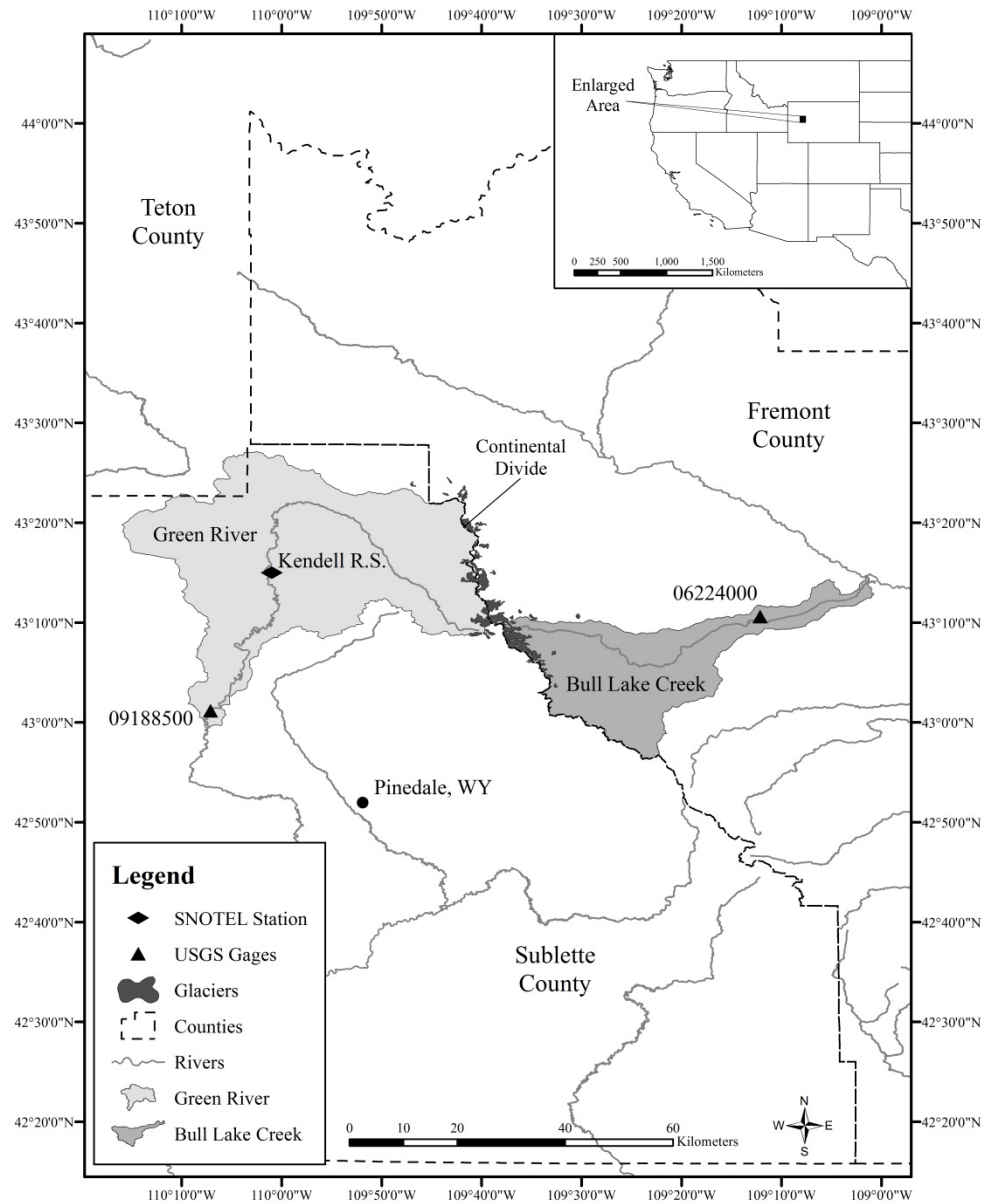


Figure 1: Location map of watersheds (Bull Lake Creek and Green River), SNOTEL stations, and USGS streamflow gages

Mark F. Meier was the first person to study the glaciers around Gannett and Fremont Peak within the Wind River Range in 1950. His study reported the surface area of Dinwoody Glacier to be approximately 3.47 km^2 (Meier, 1951). Consequently, later studies by Marston et al. (1989) and Wolken (2000) determined the area to be 2.91 km^2 and 2.19 km^2 respectively. Along with the analysis of glacier surface ice, Marston et al. (1991) utilized aerial photography stereo-pairs to determine Dinwoody Glacier lost 0.064 km^3 of water equivalent between 1958 and 1983. Wolken (2000) updated the volume loss values using aerial photography stereo-pairs from 1983 to 1994, which determined Dinwoody Glacier lost an additional 0.043 km^3 . Cheesbrough (2007) again updated these volume loss estimates for Dinwoody Glacier using aerial photography stereo-pairs from 1983 to 2001, which determined Dinwoody Glacier 0.060 km^3 . Cheesbrough et al. (2009) studied area changes for 42 glaciers in the Wind River Range using Landsat imagery (30 meter resolution) from 1985 to 2005 which showed an average loss of surface area of approximately 25%. Thompson et al. (2011) studied area changes for 44 glaciers in the Wind River Range using aerial photographs (1 meter resolution) from 1966 to 2006 which showed an average loss of surface area of approximately 38%. Bell et al. (2012) identified two glaciated and two non-glaciated watersheds in the Wind River Range and, using a paired watershed approach, examined how glaciers influence late-summer/early-fall (July-August-September) streamflow. Bell et al. (2012) determined the influence of glaciers accounted for 23–54% of the late summer (JAS) flow in glaciated watersheds. The majority of the increased flow was because of the glaciers decelerating the snowmelt runoff through internal storage/delayed release of liquid water. The glaciated watersheds provided a more stable source of streamflow because they displayed less year-to-year streamflow variability.

Thompson (2009) estimated that the percentage of July-August-September streamflow contributed by Wind River Range glacier melt varied from 2.9 to 12.4% from 1989 to 2006. This was based on volume-area scaling relationships developed by Bahr et al. (1997). However, the focus of Thompson (2009) was to assess glacier area change, and, thus, a more definitive study is required to estimate glacier volume contributions (with error) to July-August-September streamflow in the Wind River Range.

The current research expands upon previous research efforts and identified two glaciated watersheds, one on the east slope (Bull Lake Creek) and one on the west slope (Green River) of the Wind River Range in which unimpaired streamflow is available from 1966 to 2006. Glaciers were delineated within each watershed and area estimates (with error) were obtained for the years 1966, 1989 and 2006 (Thompson 2009; Thompson et al., 2011). Glacier volume (mass) loss (with error) was estimated using the volume-area scaling relationships developed by Bahr et al. (1997). These results were then compared to measured glacier mass loss using stereo-pairs and remote sensed data for glaciers in the neighboring Teton Range (Wyoming) and Dinwoody Glacier (Wind River Range, Wyoming). The percentage of glacier mass contribution (with error) to July-August-September streamflow was estimated for three periods: 1966 to 1989, 1989 to 2006, and 1966 to 2006, and, the variability of the glacier mass contributions over these periods was explained through precipitation (snowpack) and temperature datasets.

DATA

Streamflow from Glaciated Watersheds

An unimpaired stream gage station is defined as a station with minimal effects of anthropogenic uses including storage, diversion, and consumptive use. Unimpaired stations were

identified using the Hydro-Climatic Data Network (HCDN) (Slack et al., 1993; Wallis et al., 1991). United States Geological Survey (USGS) stream gage information was obtained for all stream gages in this study from the National Water Information System – NWIS (2012).

Although there are many gages recording streamflow from both slopes of the Wind River Range, it was difficult to find unimpaired stations with continuous data from glaciated watersheds (Bell et al., 2012; Barnett et al., 2010; Watson et al., 2009). The gage stations were evaluated to meet the stated criteria above and two stations were selected: West Slope – USGS Station #09188500: Green River at Warren Bridge near Daniel, WY (hereon referred to as Green River) and, East Slope – USGS Station #06224000 Bull Lake Creek above Bull Lake, WY (heron referred to as Bull Lake Creek). The Green River watershed has a drainage area of 1,212 square kilometers while the Bull Lake Creek watershed has a drainage area of 484 square kilometers. The majority of glacier melt and contribution to streamflow occurs during the late-summer / early-fall season (July-August-September) (Bell et al., 2012). Thus, this is the season of interest in the current research.

For the period of record of 1967 to 2006, the Green River gage station was missing data for the 1993 water year (October 1992 to September of 1993). To estimate streamflow for the missing water year (1993), a value of 93% of the average streamflow for the available years was used. This was determined by:

1. Bell et al. (2012) established climatic similarity between the Green River and Bull Lake Creek watersheds.

2. The correlation of yearly (1966 to 1992 and 1994 to 2006) Green River and Bull Lake Creek July-August-September or JAS (glacier meltwater season) streamflow was 0.95.

3. The 1992 JAS streamflow for Bull Lake Creek was 93% of the long term average.

For each gage, the average monthly discharge data in cubic feet per second (cfs) was converted to volume (cubic meters). This was accomplished by taking the monthly runoff in cfs and multiplying * 60 seconds/minute * 60 minutes/hour * 24 hours/day * the number of days in the month of interest (30 or 31) * 0.0283 cubic meters/cubic feet (Table 1, Appendix A).

Table 1: Total streamflow (JAS) ($\text{m}^3 \times 10^6$).

Watershed	1967-1989	1990-2006	1967-2006
Green River	3,689	2,237	5,926
Bull Lake Creek	2,625	1,702	4,327

Glacier Area

Thompson et al (2011) evaluated area change for forty-four glaciers in the Wind River Range using aerial photography (Table 2, Appendix B). Aerial photos were used due to their extremely high resolution (approximately one-meter), allowing both large and small glaciers to be examined thoroughly. The aerial photographs for this research were taken during the late summer/early fall months when snowpack has disappeared and the glacier terminus is clearly visible. Per Thompson et al (2011):

1. The aerial photos were obtained from the Wyoming Geographic Information Science Center (WyGisc) in Laramie, WY and the University of Wyoming Geology

Library in Laramie, WY. The images include aerial photographs for the years of 1966, 1989 and 2006.

2. The geo-referencing process involved assigning spatial coordinates to each non-referenced photo. Unknown spatial coordinates were estimated by digitally registering the 1966 and 1989 photos to the 2001 Fremont County compressed county mosaic (CCM) aerial photo (which was used as the “base”) to enable calculation of area change between years. All photos were geo-referenced to the Universal Transverse Mercator (UTM) zone 12 coordinate system and are tied to the North American Datum 1983 (NAD83) units. The scanned image was projected using a two to four polynomial transformation and nearest neighbor, re-sampling until the root mean square error (RMSE) of the control points equaled 0.1 or less.
3. Once RMSE was calculated for each individual geo-referenced paper photo, the RMSE was summed together with the base photo’s (2001 CCM) state average RMSE of 2.50 m. For 1966 photos, this resulted in an average RMSE of 2.57 pixels (2.57 m) and for 1989, an average RMSE of 2.55 pixels (2.55 m) was calculated. The 2006 Fremont county mosaic was pre-digitized by the United States Department of Agriculture (USDA) with a calculated RMSE value of 4.19 pixels (4.19 m).
4. Glaciers were identified and digitized by their glacier ice boundary, ice extents and stagnant ice (ice physically separated from the main glacier body). After all 44 glaciers were digitized, the surface area was calculated using the ArcGIS calculate area geometry function.

5. The methods used for digitization and delineation of glacier boundaries as well as, the calculation of area are relatively straightforward, however positional and interpreter errors are potential uncertainties that are still present. Geo-referencing area error was estimated using a method developed from Hall et al. (2003). The total error for each individual glacier's surface area was calculated from Debeer and Sharp (2007).

For the current research it is assumed the glacier aerial photos were taken in early October. These assumptions were made such that Table 1 could be developed and reflect the estimated total JAS streamflow for time periods in between when the aerial photos were taken. For example, we will assume the 1966 aerial photo is taken after September 30, 1966 and the 1989 aerial photo is taken after September 30, 1989. Thus, the total JAS streamflow in between the aerial photo dates would be 1967 thru 1989 (per Table 1). Similarly, we will assume the 1989 aerial photo is taken after September 30, 1989 and the 2006 aerial photo is taken after September 30, 2006. Thus, the total JAS streamflow in between the aerial photo dates would be 1990 thru 2006 (per Table 1). The total JAS streamflow from 1966 to 2006 would be the sum of these two, or, the total JAS streamflow for 1967 thru 2006 (per Table 1). While the aerial photographs were likely taken during August or September, this assumption simplifies the estimate of glacier meltwater as a percentage of JAS total streamflow and, given the long periods of record (23, 17 and 40 years), the small portion of streamflow was negligible.

The Green River and Bull Lake Creek watersheds were delineated and glaciers in each watershed (per Thompson et al., 2011) were identified (Figure 2). For the Green River watershed, eight glaciers were identified and for the Bull Lake Creek watershed, 12 glaciers were identified (Table 2). For the Green River watershed, glacier area within the watershed was

approximately 7.5, 6.5 and 4.8 square kilometers in 1966, 1989 and 2006, respectively. For the Bull Lake Creek watershed, glacier area within the watershed was approximately 14.7, 11.9 and 8.0 square kilometers in 1966, 1989 and 2006, respectively.

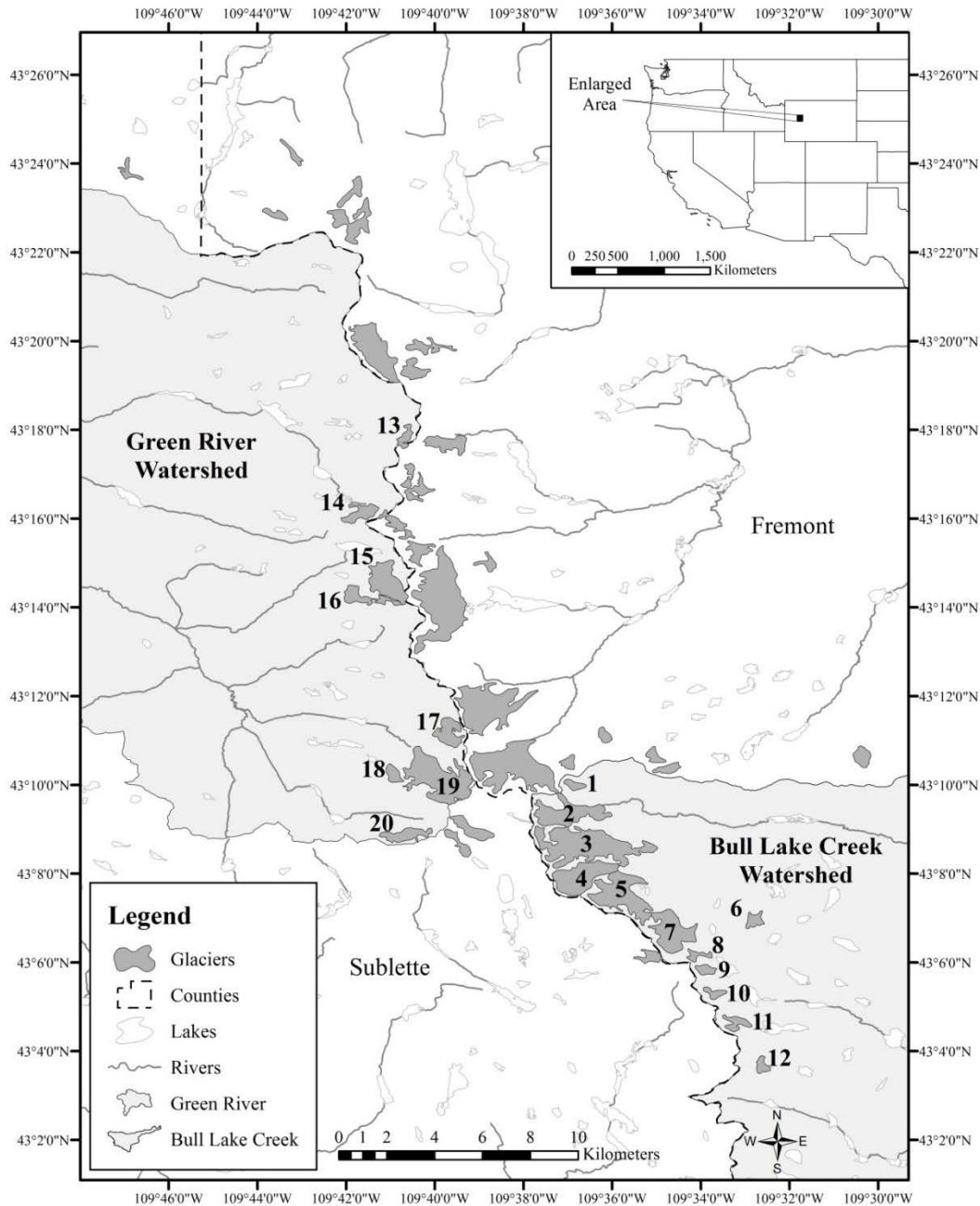


Figure 2: Location map of 20 glaciers (ID provided) in the Wind River Range

Table 2: Glacier ID, watershed, glacier name and glacier area (km²) with error for 1966, 1989 and 2006 (from Thompson et al., 2011).

Glacier ID	Watershed	Glacier Names	Glacier Surface Area (km ²)		
			1966	1989	2006
13	GR	NN	0.351 ± 0.046	0.244 ± 0.000	0.127 ± 0.004
14	GR	Connie Glacier	0.532 ± 0.011	0.510 ± 0.002	0.332 ± 0.003
15	GR	Sourdough Glacier	1.274 ± 0.018	1.139 ± 0.006	0.922 ± 0.001
16	GR	J Glacier	0.676 ± 0.053	0.506 ± 0.004	0.344 ± 0.004
17	GR	Minor Glacier	0.720 ± 0.008	0.629 ± 0.005	0.425 ± 0.004
18	GR	Baby Glacier	0.326 ± 0.002	0.287 ± 0.028	0.221 ± 0.004
19	GR	Mammoth Glacier	2.959 ± 0.064	2.558 ± 0.007	2.028 ± 0.015
20	GR	Stroud Glacier	0.638 ± 0.041	0.599 ± 0.036	0.409 ± 0.007
1	BLC	NN	0.154 ± 0.003	0.195 ± 0.003	0.147 ± 0.003
2	BLC	Helen Glacier	1.393 ± 0.040	1.494 ± 0.025	1.075 ± 0.046
3	BLC	Sacagawea Glacier	3.351 ± 0.143	3.150 ± 0.002	2.046 ± 0.030
4	BLC	Upper Fremont	2.233 ± 0.199	1.904 ± 0.014	1.306 ± 0.006
5	BLC	Bull Lake Glacier	3.195 ± 0.107	2.312 ± 0.080	1.716 ± 0.051
6	BLC	NN	0.277 ± 0.009	0.193 ± 0.007	0.174 ± 0.005
7	BLC	Knife Point Glacier	1.874 ± 0.009	1.317 ± 0.031	0.790 ± 0.004
8	BLC	NN	0.440 ± 0.007	0.394 ± 0.027	0.142 ± 0.004
9	BLC	NN	0.365 ± 0.004	0.232 ± 0.007	0.181 ± 0.003

Table 2. Continued.					
			Glacier Surface Area (km²)		
Glacier ID	Watershed	Glacier Names	1966	1989	2006
10	BLC	NN	0.399 ± 0.018	0.193 ± 0.016	0.177 ± 0.004
11	BLC	NN	0.778 ± 0.046	0.369 ± 0.011	0.176 ± 0.007
12	BLC	NN	0.225 ± 0.014	0.167 ± 0.009	0.095 ± 0.001

METHODS AND RESULTS

Methods

Several methods are available to estimate glacier volume based on glacier area (volume-area scaling relationships). It should be noted that volume-area scaling relationships are most accurate when applied to glaciers that are in equilibrium with climate. Given the Wind River Range glaciers are in recession, this may impact the estimate of glacier mass (see Discussion and Conclusions). These volume-area scaling methods determined that glacier volumes (V expressed in m^3) and areas (A expressed in m^2) could be related by a power law expressed as:

$$V = \alpha A^\beta \quad (1)$$

Chen and Ohmura (1990) derived α and β by analyzing 63 glaciers having known areas and volumes using topographic surveys and radio-echo soundings in North America, Europe and Asia. They derived α (0.120) and β (1.396) by using a regression analysis on an area versus volume plot of the glaciers. Driedger and Kennard (1986) used similar methods as Chen and Ohmura (1990) but focused more on examining the relationship between glacier flow and geometry of 25 glaciers in Washington and the Oregon Cascades. They found their relationship

was most appropriate for small alpine glaciers less than 2.6 km long when using α (3.93) and β (1.124).

A method presented by Bahr et al. (1997) was selected because of its ability to reasonably estimate smaller glacier volumes (Granshaw and Fountain, 2006). The Bahr et al. (1997) method is based on the width, slope, side drag and mass balance of 144 glaciers located in Europe, North America, central Asia and the Arctic (Bahr et al., 1997). Bahr et al. (1997) then tested the parameters against the known volumes (calculated with radio echo soundings) and the areas of each individual glacier. Bahr et al. (1997) empirically derived α and β from a regression analysis plot. Based on units, there are several variations of this equation:

$$\alpha = 0.226 \text{ when Area (A) is input as m}^2 \text{ and the resulting Volume (V) is in m}^3$$

$$\alpha = 32.7 \text{ when Area (A) is input as km}^2 \text{ and the resulting Volume (V) is in million m}^3$$

$$\alpha = 0.033 \text{ when Area (A) is input as km}^2 \text{ and the resulting Volume (V) is in km}^3$$

$$\beta = 1.36 \text{ for all variations based on the Bahr regression analysis plot}$$

For the current research, glacier area (with error) is provided for each glacier in the Green River watershed and the Bull Lake Creek watershed for 1966, 1989 and 2006 (Thompson et al., 2011). Thus, the volume of each glacier (with error) was calculated for 1966, 1989 and 2006 using the Bahr equation. To determine the glacier mass loss, three periods were selected (1966 to 1989, 1989 to 2006 and 1966 to 2006).

Results

Utilizing the glacier surface areas with error (Table 2), we can estimate the volume of each glacier in 1966, 1989 and 2006 using the Bahr equation, and, by subtracting the 2006

volume estimated from the 1966 volume estimate, we can estimate the volume (mass) of glacier loss from 1966 to 2006. This is repeated for the period of 1966 to 1989 and 1989 to 2006.

For example, to determine the volume loss for single glacier (Mammoth Glacier) in the Green River watershed from 1966 to 2006, we first determine the volume of Mammoth Glacier in 1966. For 1966, three volume calculations are performed using the estimated average glacier area (2.959 km^2), the estimated maximum glacier area ($2.959 + 0.064 = 3.023 \text{ km}^2$), and the estimated minimum glacier area ($2.959 - 0.064 = 2.895 \text{ km}^2$). Using Bahr, this resulted in 142.8, 147.1 and $138.7 \text{ m}^3 \times 10^6$, respectively. For 2006, three volume calculations are performed using the estimated average glacier area (2.028 km^2), the estimated maximum glacier area ($2.028 + 0.015 = 2.043 \text{ km}^2$), and the estimated minimum glacier area ($2.028 - 0.015 = 2.013 \text{ km}^2$). Using Bahr, this resulted in 85.5, 86.3 and $84.6 \text{ m}^3 \times 10^6$, respectively (Table 3, Appendix C).

Table 3: Glacier ID, watershed, glacier name and average, maximum and minimum glacier volume estimates (per Bahr et al., 1997) in $\text{m}^3 \times 10^6$.

Glacier ID	Watershed	Glacier Names	Average/Maximum/Minimum Glacier Volume ($\text{m}^3 \times 10^6$)		
			1966	1989	2006
13	GR	NN	7.9/9.3/6.5	4.8/4.8/4.8	2.0/2.1/1.9
14	GR	Connie Glacier	13.8/14.2/13.5	13.1/13.1/13.0	7.3/7.4/7.2
15	GR	Sourdough Glacier	45.4/46.3/44.5	39.0/39.3/38.7	29.3/29.3/29.2
16	GR	J Glacier	19.2/21.3/17.2	12.9/13.1/12.8	7.7/7.8/7.5
17	GR	Minor Glacier	20.9/21.2/20.6	17.4/17.6/17.2	10.2/10.3/10.1
18	GR	Baby Glacier	7.1/7.2/7.1	6.0/6.8/5.2	4.2/4.3/4.1
19	GR	Mammoth Glacier	142.8/147.1/138.7	117.2/117.6/116.7	85.5/86.3/84.6
20	GR	Stroud Glacier	17.7/19.3/16.2	16.3/17.6/15.0	9.7/9.9/9.5
1	BLC	NN	2.6/2.6/2.5	3.5/3.6/3.5	2.4/2.5/2.3

Table 3. Continued.					
			Average/Maximum/Minimum Glacier Volume ($\text{m}^3 \times 10^6$)		
Glacier ID	Watershed	Glacier Names	1966	1989	2006
2	BLC	Helen Glacier	51.3/53.3/49.3	56.4/57.7/55.1	36.0/38.2/34.0
3	BLC	Sacagawea Glacier	169.2/179.1/159.4	155.5/155.7/155.4	86.5/88.2/84.8
4	BLC	Upper Fremont	97.4/109.4/85.8	78.4/79.2/77.6	47.0/47.3/46.7
5	BLC	Bull Lake Glacier	158.6/165.8/151.4	102.1/107/97.3	68.1/70.9/65.3
6	BLC	NN	5.7/6.0/5.4	3.5/3.7/3.3	3.0/3.1/2.9
7	BLC	Knife Point Glacier	76.7/77.3/76.2	47.5/49.0/46.0	23.7/23.9/23.5
8	BLC	NN	10.7/10.9/10.5	9.2/10.1/8.4	2.3/2.4/2.2
9	BLC	NN	8.3/8.4/8.2	4.5/4.7/4.3	3.2/3.3/3.1
10	BLC	NN	9.4/9.9/8.8	3.5/3.9/3.1	3.1/3.2/3.0
11	BLC	NN	23.2/25.1/21.4	8.4/8.8/8.1	3.1/3.2/2.9
12	BLC	NN	4.3/4.7/3.9	2.9/3.1/2.7	1.3/1.3/1.3

To determine the estimated volume loss (with error), three volumes were calculated. First, the 2006 average volume ($85.5 \text{ m}^3 \times 10^6$) was subtracted from the 1966 average volume ($142.8 \text{ m}^3 \times 10^6$) which resulted in $57.3 \text{ m}^3 \times 10^6$. Next, the 2006 minimum volume ($84.6 \text{ m}^3 \times 10^6$) was subtracted from the 1966 maximum volume ($147.1 \text{ m}^3 \times 10^6$) which resulted in $63.1 \text{ m}^3 \times 10^6$. Finally, the 2006 maximum volume ($86.3 \text{ m}^3 \times 10^6$) is subtracted from the 1966 minimum volume ($138.7 \text{ m}^3 \times 10^6$) which resulted in $52.4 \text{ m}^3 \times 10^6$. Thus, for Mammoth Glacier, the estimated glacier volume (mass) loss ranged from $52.4 \text{ m}^3 \times 10^6$ to $63.1 \text{ m}^3 \times 10^6$ with an average loss of $57.3 \text{ m}^3 \times 10^6$. This was repeated for each glacier in the Green River and Bull Lake Creek watersheds and the total volume (mass) for the average, maximum and minimum were summed for each glacier, for each period (Table 4, Appendix C). These values were then divided by the

total JAS streamflow (see Table 1) for each watershed, for each period to determine the percentage of glacier volume (mass) contributing to streamflow.

Table 4: Watershed, average, maximum and minimum total glacier volume estimates ($\text{m}^3 \times 10^6$) for 1966-1989, 1989-2006 and 1996-2006, and percentage of JAS streamflow.

		Estimated Glacier Volume ($\text{m}^3 \times 10^6$) and percentage of JAS streamflow		
Watershed	Avg, Mx, Min	1966-1989	1989-2006	1966-2006
GR	Average	48.3(1.3%)	70.9 (3.2%)	119.2 (2.0%)
GR	Maximum	62.4 (1.7%)	75.8 (3.4%)	131.8 (2.2%)
GR	Minimum	34.3 (0.9%)	66.1 (3.0%)	106.8 (1.8%)
BLC	Average	141.8 (5.4%)	195.7 (11.5%)	337.6 (7.8%)
BLC	Maximum	187.7 (7.2%)	214.2 (12.6%)	380.4 (8.8%)
BLC	Minimum	96.5 (3.7%)	177.3 (10.4%)	295.4 (6.8%)

DISCUSSION AND CONCLUSIONS

There are several interesting observations with regards to JAS streamflow and the influence of glaciers. Referring to Table 1, for the various periods of record, the JAS streamflow for the Bull Lake Creek watershed was 71% to 76% of the JAS streamflow for the Green River watershed. However, the Bull Lake Creek watershed area (484 km^2) is smaller (approximately 40%) than the Green River watershed area ($1,212 \text{ km}^2$) and both watersheds experience similar climatic influences (Bell et al., 2012). This is likely explained by the higher percentage of glacier coverage in Bull Lake Creek (1966 – 3.0% and 2006 – 1.7%) when compared to Green River (1966 – 0.6% and 2006 – 0.4%) (Table 2). Bell et al (2012) observed that the impacts of glaciers on local streamflows during JAS were shown to be much greater than glacier melt alone and glaciers accounted for 23% to 54% of the late summer (JAS) flow in glaciated watersheds due to the glaciers decelerating the snowmelt runoff through internal storage/delayed release of

liquid water. When comparing annual streamflow, the Bull Lake Creek watershed annual streamflow was 58% of the Green River watershed annual streamflow. Thus, the annual streamflow comparison was more in line with the watershed area scaling relationship (40%).

Referring to Table 4, the contribution (percentage) of glacier volume (mass) was greatest during the 1989 to 2006 period for both watersheds. Historic records of observed precipitation (snowpack) and temperature were investigated (Appendix D). The Natural Resource Conservation Service (NRCS) maintains an extensive data collection system (SNOwpack TELemetry or SNOTEL) in the western United States in which snowpack (Snow Water Equivalent – SWE) is collected (NRCS, 2012). The Kendall R.S. station, located in the Green River watershed (Figure 1) was selected and has been utilized in previous research efforts (Aziz et al., 2010; Hunter et al., 2006). April 1st snow water equivalent, which typically represents the peak snowpack accumulation, was accessed and yearly values were plotted with a 10-year filter (10-year running average) (Figure 3). The United States Historical Climatology Network (USHCN) is a high-quality data set of daily and monthly records of basic meteorological variables from 1218 observing stations across the 48 contiguous United States (USHCN, 2012; Easterling et al., 1996). Monthly data were accessed from Pinedale, Wyoming (Figure 1) and yearly JAS average temperatures were calculated and plotted with a 10-year filter (10-year running average) (Figure 3). The increased contribution of glacier mass from 1989 to 2006 is most likely associated with rapid JAS temperature increases and lower snowpack when compared to historical averages (Figure 3). Edmunds et al. (2012) observed similar temperature and snowpack patterns in the Teton Range (Wyoming), located approximately 150 kilometers from the Wind River Range.

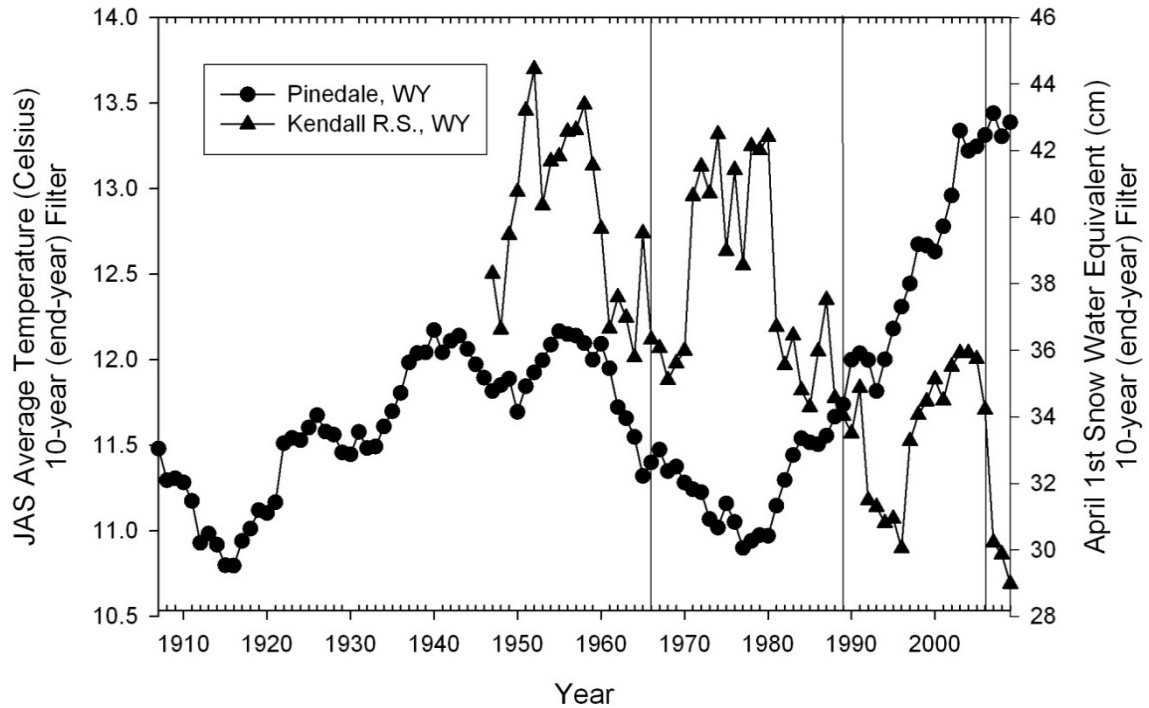


Figure 3: April 1st Snow Water Equivalent (cm) from the Kendall R.S. (Wyoming) SNOTEL station and JAS average temperatures (Celsius) from Pinedale (Wyoming). A 10-year filter was applied to each dataset.

When referring to Table 4, glacier mass contributions to JAS streamflow was approximately 2% for the Green River watershed and 8% for the Bull Lake Creek watershed. As previously discussed, this difference is most likely attributed to increased glacier coverage in the Bull Lake Creek watershed. The Bahr equation has been found to be most effective when glaciers are in equilibrium with climate. Obviously, this is not the case with Wind River Range glaciers as they are in a state of recession. Edmunds et al. (2012) utilized stereo-pairs and remote sensed data to measure ice (glacier) mass loss in the Teton Range. Three glaciers (Teton, Middle Teton and Teepe) were evaluated and it was estimated that these glaciers lost $3.2 \times 10^6 \text{ m}^3$ ($\pm 0.46 \times 10^6 \text{ m}^3$) from 1967 to 2002. Glacier area data (with error) was obtained for the three glaciers for 1967 and 2002. This data was input into the Bahr equation to estimate glacier

mass loss for comparison. Using the Bahr equation, these glaciers lost $2.8 \times 10^6 \text{ m}^3$ ($\pm 0.43 \times 10^6 \text{ m}^3$) from 1967 to 2002. Thus, the Bahr equation slightly (about 88%) underestimated glacier mass loss when compared to measured values. Cheesbrough (2007) utilized similar techniques (stereo-pairs and remote sensed data) to measure ice (glacier) mass loss for Dinwoody glacier in the Wind River Range for 1983 to 2001. It was estimated that $60 \times 10^6 \text{ m}^3$ of glacier mass was lost from 1983 to 2001. Using the Bahr equation, it was estimated that $50 \times 10^6 \text{ m}^3$ of glacier mass was lost from 1983 to 2001 (Cheesbrough et al., 2009). Thus, a similar slight underestimation of glacier mass loss was observed. Based on these comparisons, it was concluded that the Bahr equation provides an adequate estimate of mass loss in Wind River Range glaciers, despite the glaciers being in recession.

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Appendices

Appendix A

Streamflow Data (cfs) for Green River at Warren Bridge near Daniel, WY. Please note, the “blue” identifiers in September 1966, 1989 and 2006 represent the approximate time the USGS aerial photographs of the glaciers were taken.

Website:

http://waterdata.usgs.gov/nwis/monthly/?referred_module=sw&site_no=09188500&por_09188500_7=802361,00060,7,1931-10,2011-10&format=html_table&date_format=YYYY-MM-DD&rdb_compression=file&submitted_form=parameter_selection_list

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1966	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs
1967	175.5	166.4	127.9	159.4	921.1	2,052	2,082	728.4	315.1	244.5	146.9	132.2
1968	137.5	129.4	169.3	189.3	567	1,854	1,200	883	504	285.4	185.3	129.7
1969	156	124.6	131	507.3	1,622	1,408	1,076	578.6	260.3	163.5	104.3	75.7
1970	93	109.3	121.6	129	927.8	1,877	1,099	423.1	294.5	164.2	142	146.9
1971	121.8	97.5	117.2	180.8	1,312	3,163	1,624	804	384.7	222.3	185.6	118.5
1972	121.7	113.5	165.5	291.3	1,483	3,039	1,235	677.2	395.3	290.7	202.7	139.9
1973	123.3	117.1	118.3	146.4	1,112	1,297	994.9	488.1	357.4	193.5	158.3	118.5
1974	117.8	116.3	122.8	315.9	1,368	2,812	1,289	444.4	209.9	145.2	112.2	111.4
1975	103.3	102.7	109.5	158.2	509.9	1,552	2,424	621.1	247.1	168.6	151.7	111.9
1976	109.5	99.3	101.1	225.3	1,437	1,676	1,495	590.8	285.3	178.1	113	109.5
1977	73.9	85.3	74.1	221	268.5	1,083	522.2	351.5	288.4	165.8	124.1	104.2
1978	95.7	95.7	108.5	314.8	947.2	2,017	1,653	622.9	335.2	177.3	123.9	113.6
1979	100	110.1	118	273.5	963.8	1,205	732.8	503.7	227.8	152.8	110.7	107.7
1980	82.2	102.9	110.8	263.3	1,135	1,668	1,203	395	262.2	167.1	121.7	125
1981	117	87	100.4	251.3	627.1	1,385	773.5	322	192.6	162.7	116.1	110.6
1982	106.2	116.1	138.8	308.4	1,177	2,026	2,102	997.4	471	392.8	223.2	162.6
1983	109.1	107.7	138.4	246.4	711.9	2,099	1,684	941.8	514.5	433.2	215.6	138.1
1984	156.8	131.4	126.5	227.5	1,092	1,739	1,667	692.8	410.3	326.2	198.5	130.6
1985	106.5	122.5	142.1	323.5	1,061	1,152	692.2	312.3	289.5	228.8	200.2	158.7
1986	108.1	141.2	161.3	364.7	1,404	3,813	1,607	685.2	338	226	182.9	137.5
1987	114.7	132.5	173.9	568.5	1,142	1,034	746.9	497.7	283.6	148.6	122.3	102.4
1988	93.7	104.5	109.6	344.1	797.5	1,261	399.5	213.4	149.6	102.1	99.2	115.7
1989	105.1	99.5	135.8	312.4	751.3	1,318	1,171	376.7	207.2	151.8	112.8	128.7
1990	97.2	85.2	111.5	339.5	539.6	1,461	1,094	399.6	265.6	180.1	142.6	106.1
1991	102.4	121.1	129	250.7	1,047	1,904	983.7	493.6	381.6	166.2	146.1	93.7
1992	92.8	114.7	150	274.4	765.5	734.9	512.1	289.3	190.1			
1993										183.4	67.7	105.7
1994	101.9	91.9	111.5	390.8	1,006	950.6	446.2	331.1	208.7	198.5	129	99.3
1995	92.3	105.2	131.6	222.6	484.2	2,155	2,097	702.3	313.3	175.8	166.8	183.2
1996	126.7	110.7	123.8	285.2	1,193	2,854	1,754	631.2	306.1	175.1	154.2	214.8
1997	160	121.4	136.8	251.7	1,494	3,303	1,301	687.8	490	327.8	195.7	131.9
1998	119.9	117.9	130.3	254.8	1,328	1,537	1,833	605.6	373	268.1	210.2	158.6
1999	158.2	139.4	149	266.4	1,018	2,212	1,393	541.5	309.5	160.6	143.5	164.9
2000	136.7	130.5	151.1	426.8	1,035	1,229	633.8	334.9	239.7	159.7	106.1	104.2
2001	97.7	91.9	127.9	231	820.3	741.5	476.9	229.6	159.3	117.2	114.9	71
2002	57.9	69.7	95	229.6	496.5	1,430	708	263.1	284.1	163.4	148.7	106.5
2003	96	92.8	127.6	397.1	854.2	1,474	884.9	419	345.1	160.5	118.6	112.9
2004	95.5	93	206.5	285.1	510.5	1,241	1,149	434.6	293.2	216.9	141.1	119.1
2005	108	94	99.1	369.3	1,195	1,544	1,067	326.5	163.3	143.2	163.8	122.5
2006	111.1	77.8	97.3	302.3	1,238	1,539	659.8	259.5	163.6	190.3	116.3	90.8

Total flow (cubic meters) for July-August-September (JAS):

	Jul	Aug	Sep	Jul	Aug	Sep	JAS		
	cfs	cfs	cfs	cubic meters	cubic meters	cubic meters	cubic meters		
1966									
1967	2,082	728.4	315.1	152,722,195	55,211,788	23,113,719	231,047,702		
1968	1,200	883	504	88,024,320	66,930,270	36,970,214	191,924,804		
1969	1,076	578.6	260.3	78,928,474	43,857,139	19,093,942	141,879,555		
1970	1,099	423.1	294.5	80,615,606	32,070,438	21,602,635	134,288,680		
1971	1,624	804	384.7	119,126,246	60,942,171	28,219,130	208,287,547		
1972	1,235	677.2	395.3	90,591,696	51,330,893	28,996,678	170,919,267		
1973	994.9	488.1	357.4	72,979,497	36,997,355	26,216,577	136,193,429		
1974	1,289	444.4	209.9	94,552,790	33,684,951	15,396,921	143,634,662		
1975	2,424	621.1	247.1	177,809,126	47,078,585	18,125,675	243,013,386		
1976	1,495	590.8	285.3	109,663,632	44,781,884	20,927,782	175,373,298		
1977	522.2	351.5	288.4	38,305,250	26,643,250	21,155,178	86,103,678		
1978	1,653	622.9	335.2	121,253,501	47,215,023	24,588,127	193,056,650		
1979	732.8	503.7	227.8	53,753,518	38,179,815	16,709,950	108,643,283		
1980	1,203	395	262.2	88,244,381	29,940,494	19,233,314	137,418,189		
1981	773.5	322	192.6	56,739,010	24,407,188	14,127,903	95,274,101		
1982	2,102	997.4	471	154,189,267	75,601,643	34,549,546	264,340,456		
1983	1,684	941.8	514.5	123,527,462	71,387,234	37,740,427	232,655,124		
1984	1,667	692.8	410.3	122,280,451	52,513,353	30,096,982	204,890,786		
1985	692.2	312.3	289.5	50,775,362	23,671,940	21,235,867	95,683,169		
1986	1,607	685.2	338	117,879,235	51,937,283	24,793,517	194,610,035		
1987	746.9	497.7	283.6	54,787,804	37,725,023	20,803,081	113,315,908		
1988	399.5	213.4	149.6	29,304,763	16,175,447	10,973,699	56,453,909		
1989	1,171	376.7	207.2	85,897,066	28,553,378	15,198,866	129,649,309	3,688,656,929	Total from 67 thru 89
1990	1,094	399.6	265.6	80,248,838	30,289,169	19,482,716	130,020,723		
1991	983.7	493.6	381.6	72,157,936	37,414,248	27,991,734	137,563,918		
1992	512.1	289.3	190.1	37,564,379	21,928,570	13,944,519	73,437,468		
1993				-	-	-	134,640,829		93% of average
1994	446.2	331.1	208.7	32,730,376	25,096,956	15,308,896	73,136,229		
1995	2,097	702.3	313.3	153,822,499	53,233,441	22,981,683	230,037,623		
1996	1,754	631.2	306.1	128,662,214	47,844,152	22,453,537	198,959,903		
1997	1,301	687.8	490	95,433,034	52,134,360	35,943,264	183,510,657		
1998	1,833	605.6	373	134,457,149	45,903,705	27,360,893	207,721,746		
1999	1,393	541.5	309.5	102,181,565	41,045,007	22,702,939	165,929,511		
2000	633.8	334.9	239.7	46,491,512	25,384,991	17,582,858	89,459,361		
2001	476.9	229.6	159.3	34,982,332	17,403,386	11,685,228	64,070,946		
2002	708	263.1	284.1	51,934,349	19,942,643	20,839,758	92,716,750		
2003	884.9	419	345.1	64,910,601	31,759,664	25,314,327	121,984,592		
2004	1,149	434.6	293.2	84,283,286	32,942,124	21,507,276	138,732,686		
2005	1,067	326.5	163.3	78,268,291	24,748,282	11,978,643	114,995,216		
2006	659.8	259.5	163.6	48,398,705	19,669,768	12,000,649	80,069,122	2,236,987,281	Total from 90 thru 06
								5,925,644,210	Total from 67 thru 06

Streamflow Data (cfs) for Bull Lake Creek above Bull Lake, WY. Please note, the “blue” identifiers in September 1966, 1989 and 2006 represent the approximate time the USGS aerial photographs of the glaciers were taken.

Website:

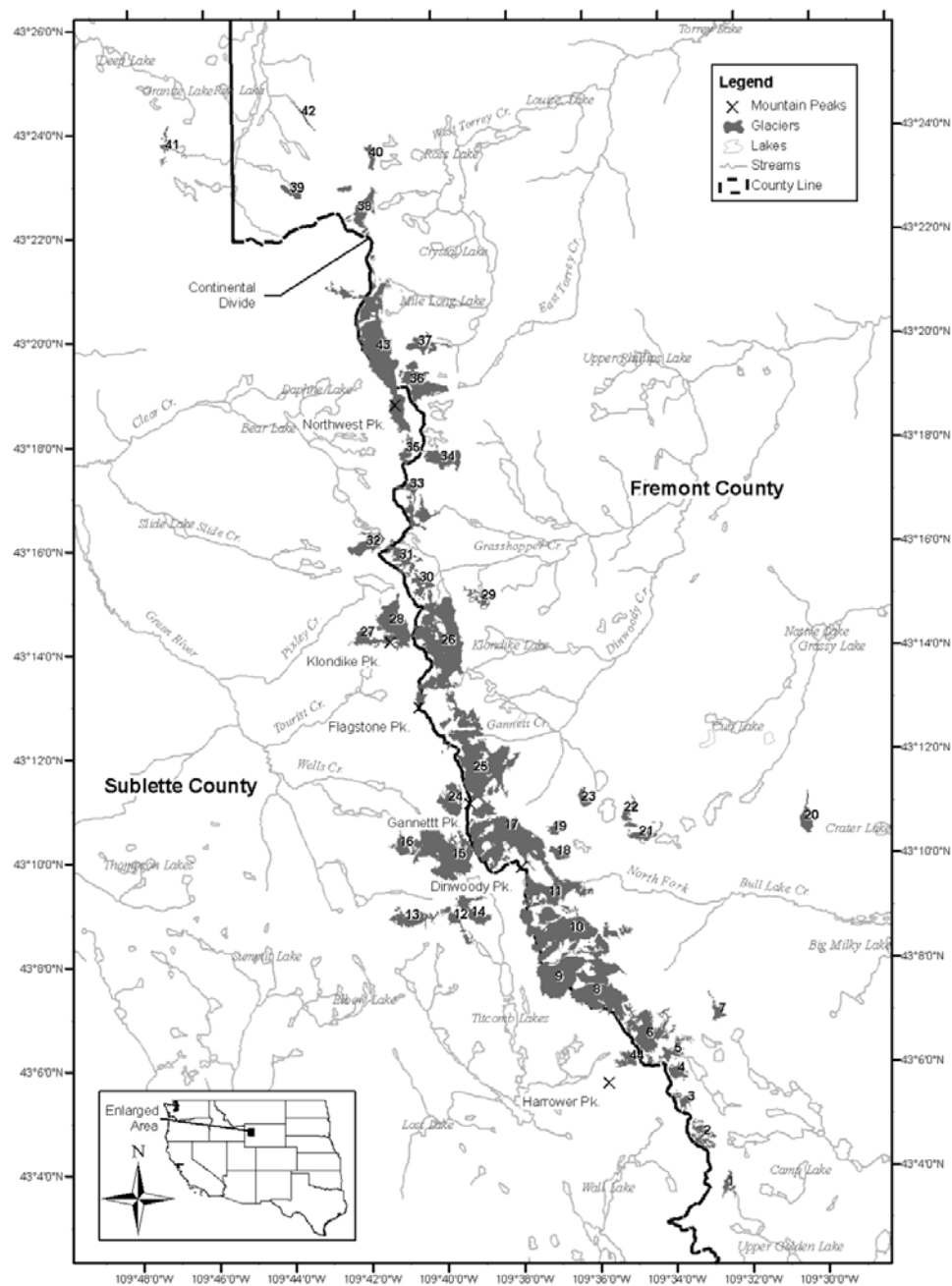
http://waterdata.usgs.gov/nwis/monthly/?referred_module=sw&site_no=06224000&por_06224000_1=801584,00060,1,1941-10,2012-05&format=html_table&date_format=YYYY-MM-DD&rdb_compression=file&submitted_form=parameter_selection_list

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1966	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs
1967	36.1	29.5	27.7	40.5	505.4	1372	1462	488.7	237.5	184.5	70.5	41.2
1968	23.9	24.3	27.8	39.4	225.8	1214	778.6	619.8	226.4	127.7	69.5	36.4
1969	37	39.9	29.5	98.7	776.6	1126	838.4	448.6	161.1	72	36	19.1
1970	19.5	25.3	19.3	24.9	439.7	1167	735.4	361.1	178.5	60.6	40.8	49.4
1971	38.2	26.4	23.6	46	439.6	1924	1043	555.5	241.7	127.4	67.3	37.4
1972	38.1	33.6	42	61.8	312.8	1637	880.1	497.4	214.4	129.9	58.2	33.1
1973	28.5	23.6	21	32.6	423.4	961.3	776.5	433.5	533.4	146.6	103.7	48.4
1974	32	29.7	34.6	78.6	506.3	1495	864.8	345.7	157.4	58.4	36.3	20.7
1975	17.9	18	23.7	31.6	170.4	875.1	1581	372.4	149.9	62	37.5	30.8
1976	23.2	18.7	25.1	42.8	555.4	957.3	946.8	412.5	193.9	79.6	29.5	14.6
1977	7.29	6.88	6.69	28.7	215	684.1	480.5	337.5	194	81.3	48.9	49.4
1978	29.4	20.5	24.3	52	361.9	1305	1118	417.4	192.1	66.4	33.6	31.9
1979	26.2	27.5	24.4	37.1	541.8	818.1	620.2	411.2	203.6	83.2	37.9	19
1980	15.9	20.3	19.7	79.6	627.3	1385	1056	301.8	139	63.5	38.5	32.8
1981	20.8	17.2	18.7	55.6	481.1	1222	587.7	319.5	159	79.9	55.3	42.9
1982	35.3	18.4	19.1	34	331.3	1120	1336	655.2	318.6	222.1	74.7	54.1
1983	36.4	22.6	29.1	56.6	303.2	1701	1300	645.7	278.3	149.7	82.8	54.7
1984	27.7	20.3	18.8	41.9	519.4	932.5	1002	466.3	261.2	134	63.4	35.6
1985	23.3	19.5	20.9	76.4	536.8	850.7	385.3	144.9	135.1	93	63.2	50.3
1986	27.2	39.5	57.4	167.9	607.5	2104	1064	512.3	185.7	115	73.2	40.5
1987	24.3	20.5	21.7	132.1	734.7	747.4	743.2	354.7	181.7	71.4	34.4	27.6
1988	22.6	20.1	20.6	84.8	468.7	777.5	418.5	236.4	109.2	32.9	33	25.4
1989	24.1	16.1	25.5	84.9	395.9	1033	950	353.8	146.5	105.2	56.6	33
1990	25	21.9	20	117.5	246.1	892.3	721.2	339	280.9	120.5	75.1	34.4
1991	23.2	20	24.5	46.6	574.5	1653	779.9	441.5	279.1	82	58.6	38.7
1992	21.5	15.7	18.4	60.4	513.5	559.9	409.4	273.8	122.3	67.5	40.9	32.5
1993	27.2	20.6	23	31.6	671	989.6	642	551.8	160.6	77.1	35	20.5
1994	12.3	11.6	16.8	76.4	584.5	590.3	337.5	293.6	130.2	106.1	54.4	42.7
1995	29.3	22.7	35.3	46.8	214.2	1554	1511	545	243	88.8	54.8	46.9
1996	36.6	28.1	30.1	67.5	406.7	1462	1027	388.7	168.6	62.1	44.8	53
1997	57.1	30.5	30.8	57.7	573.8	1612	837.6	626.9	362.1	136.2	65.1	36
1998	38.7	29	37	68.4	462	895.7	1420	526.4	262.8	113.5	66	33.8
1999	27.1	40	31.8	100.5	584.3	1707	1152	459.6	233	76.9	34.2	25.5
2000	23.6	22.8	21.3	73.2	612.8	836.8	521.1	339.2	166.3	69.5	32.2	21.1
2001	16.6	12.6	13.5	31.9	561.5	543.6	421.2	263.2	124.4	51.4	33.8	31.3
2002	18	16.8	15.7	29.5	267.9	895.8	532.8	201.6	144.8	64.2	39.2	23.9
2003	18.6	22.9	28.9	60.6	492.2	856.3	606.6	301.8	137.2	50.7	35.2	25.5
2004	25.8	14.6	15.8	72.9	347.6	875.7	860.1	383.9	248.7	166.5	97.3	51.1
2005	46.6	29.9	23.6	64	707.4	1187	876.7	308.8	112.2	67.4	51.1	30.9
2006	31.4	21.5	19.6	54.9	598.7	876	578.2	223.3	111.2	109.1	48.9	24.9

Appendix B

From Thompson et al (2011):

- (a) Figure identifying 44 glaciers in which area was estimated using aerial photographs for 1966, 1989, and 2006
- (b) Glacier information
- (c) Glacier area with error



(a)

Site ID	Glacier Names	Latitude	Longitude	Aspect (°)	Slope (%)	Elevation (m)		
						Min	Max	Mean
1	NN	43.0613	-109.5441	144.9	17.1	3545	3724	3629
2	NN	43.0758	-109.5546	115.1	26.8	3349	3917	3658
3	NN	43.0865	-109.5648	148.3	36.2	3508	3899	3717
4	NN	43.0965	-109.5678	119.9	33.5	3550	3895	3728
5	NN	43.1029	-109.5710	138.5	28.3	3481	3945	3756
6	Knife Point Glacier	43.1117	-109.5797	109.0	22.3	3359	3947	3592
7	NN	43.1165	-109.5478	93.8	28.6	3403	3867	3560
8	Bull Lake Glacier	43.1225	-109.5995	122.7	24.9	3507	4118	3789
9	Upper Fremont	43.1314	-109.6143	120.6	17.7	3676	4178	3966
10	Sacagawea Glacier	43.1439	-109.6124	114.4	19.6	3397	4125	3716
11	Helen Glacier	43.1566	-109.6192	103.8	23.2	3418	4147	3712
12	NN	43.1451	-109.6593	124.3	21.1	3417	3848	3590
13	Stroud Glacier	43.1481	-109.6788	132.1	28.8	3425	3910	3610
14	Twins Glacier	43.1499	-109.6532	89.2	22.5	3345	3838	3557
15	Mammoth Glacier	43.1684	-109.6671	188.3	19.1	3386	4016	3680
16	Baby Glacier	43.1704	-109.6843	176.0	28.3	3423	3908	3609
17	Dinwoody Glacier	43.1716	-109.6385	146.8	22.3	3390	4147	3687
18	NN	43.1671	-109.6154	97.4	23.3	3742	4017	3829
19	Heap Steep Glacier	43.1749	-109.6179	69.1	36.5	3459	3959	3656
20	NN	43.1780	-109.5070	77.3	16.6	3508	3761	3669
21	NN	43.1720	-109.5799	130.4	29.7	3509	3953	3728
22	NN	43.1776	-109.5851	91.1	29.7	3667	4012	3757
23	NN	43.1849	-109.6059	125.7	17.0	3803	4000	3862

24	Minor Glacier	43.1856	-109.6626	205.0	24.8	3495	4054	3696
25	Gannett Glacier	43.1992	-109.6520	102.0	21.2	3343	4199	3768
26	Grasshopper Glacier	43.2355	-109.6659	130.8	14.6	3345	4087	3704
27	J Glacier	43.2368	-109.6945	198.4	26.0	3532	3991	3771
28	Sourdough Glacier	43.2430	-109.6865	167.0	16.8	3581	3942	3691
29	NN	43.2500	-109.6490	79.0	28.1	3432	3734	3612
30	NN	43.2543	-109.6747	63.5	23.6	3378	3754	3559
31	NN	43.2635	-109.6832	118.9	15.2	3502	3898	3766
32	Connie Glacier	43.2682	-109.6972	150.1	24.2	3522	3884	3708
33	NN	43.2823	-109.6791	132.1	18.4	3472	3975	3772
34	Downs Glacier	43.2959	-109.6645	90.1	23.6	3392	3937	3677
35	NN	43.2983	-109.6809	185.3	26.2	3646	3943	3812
36	NN	43.3196	-109.6727	96.1	18.7	3545	4027	3742
37	NN	43.3304	-109.6712	65.3	28.0	3298	3875	3696
38	NN	43.3755	-109.6986	88.5	11.1	3568	3757	3658
39	NN	43.3808	-109.7282	157.7	13.2	3509	3637	3600
40	NN	43.3919	-109.6939	94.4	4.7	3560	3597	3573
41	NN	43.3949	-109.7831	80.2	23.4	3276	3524	3422
42	NN	43.4062	-109.7227	259.2	13.9	3244	3487	3363
43	Continental Glacier	43.3313	-109.6903	97.3	12.7	3291	4028	3814
44	Harrower Glacier	43.1015	-109.5889	225.6	23.2	3496	3794	3634

(b)

		Glacier Surface Area (km ²)		
Site ID	Glacier Names	1966	1989	2006
1	NN	0.225 ± 0.014	0.167 ± 0.009	0.095 ± 0.001
2	NN	0.778 ± 0.046	0.369 ± 0.011	0.176 ± 0.007
3	NN	0.399 ± 0.018	0.193 ± 0.016	0.177 ± 0.004
4	NN	0.365 ± 0.004	0.232 ± 0.007	0.181 ± 0.003
5	NN	0.440 ± 0.007	0.394 ± 0.027	0.142 ± 0.004
6	Knife Point Glacier	1.874 ± 0.009	1.317 ± 0.031	0.790 ± 0.004
7	NN	0.277 ± 0.009	0.193 ± 0.007	0.174 ± 0.005
8	Bull Lake Glacier	3.195 ± 0.107	2.312 ± 0.080	1.716 ± 0.051
9	Upper Fremont	2.233 ± 0.199	1.904 ± 0.014	1.306 ± 0.006
10	Sacagawea Glacier	3.351 ± 0.143	3.150 ± 0.002	2.046 ± 0.030
11	Helen Glacier	1.393 ± 0.040	1.494 ± 0.025	1.075 ± 0.046
12	NN	0.295 ± 0.001	0.246 ± 0.008	0.142 ± 0.003
13	Stroud Glacier	0.638 ± 0.041	0.599 ± 0.036	0.409 ± 0.007
14	Twins Glacier	0.553 ± 0.007	0.535 ± 0.039	0.385 ± 0.009
15	Mammoth Glacier	2.959 ± 0.064	2.558 ± 0.007	2.028 ± 0.015
16	Baby Glacier	0.326 ± 0.002	0.287 ± 0.028	0.221 ± 0.004
17	Dinwoody Glacier	3.453 ± 0.147	2.920 ± 0.052	2.474 ± 0.054
18	NN	0.154 ± 0.003	0.195 ± 0.003	0.147 ± 0.003
19	Heap Steep Glacier	0.212 ± 0.003	0.137 ± 0.007	0.109 ± 0.002
20	NN	0.390 ± 0.001	0.347 ± 0.004	0.286 ± 0.005
21	NN	0.359 ± 0.018	0.286 ± 0.088	0.133 ± 0.010
22	NN	0.271 ± 0.010	0.234 ± 0.005	0.0986 ± 0.001
23	NN	0.269 ± 0.003	0.189 ± 0.001	0.159 ± 0.003

24	Minor Glacier	0.720 ± 0.008	0.629 ± 0.005	0.425 ± 0.004
25	Gannett Glacier	4.801 ± 0.149	3.957 ± 0.029	3.270 ± 0.025
26	Grasshopper Glacier	3.927 ± 0.064	3.558 ± 0.051	2.480 ± 0.026
27	J Glacier	0.676 ± 0.053	0.506 ± 0.004	0.344 ± 0.004
28	Sourdough Glacier	1.274 ± 0.018	1.139 ± 0.006	0.922 ± 0.001
29	NN	0.218 ± 0.002	0.200 ± 0.005	0.087 ± 0.003
30	NN	0.296 ± 0.009	0.334 ± 0.001	0.286 ± 0.005
31	NN	0.582 ± 0.024	0.527 ± 0.008	0.275 ± 0.016
32	Connie Glacier	0.532 ± 0.011	0.510 ± 0.002	0.332 ± 0.003
33	NN	1.037 ± 0.082	0.701 ± 0.000	0.442 ± 0.003
34	Downs Glacier	0.620 ± 0.028	0.598 ± 0.003	0.518 ± 0.003
35	NN	0.351 ± 0.046	0.244 ± 0.000	0.127 ± 0.004
36	NN	0.950 ± 0.020	1.033 ± 0.002	0.770 ± 0.011
37	NN	0.382 ± 0.000	0.373 ± 0.003	0.246 ± 0.000
38	NN	0.604 ± 0.014	0.659 ± 0.001	0.389 ± 0.008
39	NN	0.205 ± 0.000	0.181 ± 0.002	0.146 ± 0.000
40	NN	0.147 ± 0.006	0.165 ± 0.000	0.010 ± 0.000
41	NN	0.252 ± 0.097	0.165 ± 0.006	0.051 ± 0.001
42	NN	0.093 ± 0.017	0.070 ± 0.000	0.039 ± 0.001
43	Continental Glacier	3.501 ± 0.039	3.630 ± 0.011	2.671 ± 0.009
44	Harrower Glacier	0.306 ± 0.003	0.275 ± 0.004	0.141 ± 0.002
	Total	45.9 ± 1.6	39.7 ± 0.7	28.5 ± 0.4

(c)

Appendix C

- (a) Green River watershed estimates of glacier mass using Bahr equation.
(b) Bull Lake Creek watershed estimates of glacier mass using Bahr equation.

[illegible]

(a)

Appendix D

- (a) SNOTEL data for Kendal, R.S. site in Wyoming, USA
 (b) Monthly temperature for Pinedale, Wyoming

Raw SNOTEL Data for Kendal R.S. Pillow, Station 10F15S (Snow Water Equivalent, SWE, inches)																	
Year - Card	January			February			March			April			May			June	
	date	dep	swe	date	dep	swe	date	dep	swe	date	dep	swe	date	dep	swe	date	swe
36-1							E/ST		20.3	E/ST		25.3	E/ST		12.5		
37-1													E/ST		9.3		
38-1										E/ST		16.0	E/ST		5.8		
39-1										E/ST		10.2					
40-1										E/ST		13.4	E/ST		4.1		
41-1										E/ST		11.8	E/ST		14.1		
42-1							E/ST		10.5	E/ST		11.8	E/ST		4.8		
43-1							E/ST		33.8	E/ST		30.5	E/ST		14.7		
44-1							E/ST		6.5	E/ST		11.0					
45-1							E/ST		8.0	E/ST		11.3	E/ST		10.8		
46-1							E/ST		16.4	E/ST		17.8	E/ST		6.4		
47-1							E/ST		15.5	E/ST		17.0	E/ST		14.7		
48-1							E/ST		8.3	E/ST		9.4	E/ST		8.0		
49-1							E/ST		17.8	E/ST		21.4	E/ST		14.6		
50-1							E/ST		15.2	E/ST		18.5	E/ST		17.1		
51-1							E/ST		18.6	E/ST		21.4	E/ST		19.1		
52-1							E/ST		16.1	E/ST		16.7					
53-1							E/ST		18.3	E/ST		14.4	E/ST		11.3		
54-1							E/ST		9.6	E/ST		16.2	E/ST		5.9		
55-1							E/ST		9.6	E/ST		11.9	E/ST		7.2		
56-1				E/ST		14.2	E/ST		17.0	E/ST		20.7	E/ST		17.4		
57-1				E/ST		9.3	E/ST		11.8	E/ST		17.2	E/ST		17.8		
58-1				E/ST		8.6	E/ST		11.0	E/ST		12.4	E/ST		9.7		
59-1				E/ST		9.0	E/ST		12.9	E/ST		14.2	E/ST		9.6		
60-1				E/ST		3.1	E/ST		6.9	E/ST		11.0					
61-1				E/ST		4.9	E/ST		7.1	E/ST		9.6	E/ST		5.4		
62-1				E/ST		14.3	E/ST		20.4	E/ST		20.4	E/ST		9.8		
63-1				E/ST		4.6	E/ST		10.3	E/ST		12.0	E/ST		13.7		
64-1				E/ST		7.6	E/ST		8.8	E/ST		11.5	E/ST		10.7		
65-1				E/ST		18.0	E/ST		19.7	E/ST		26.6	E/ST		18.8		
66-1				E/ST		6.8	E/ST		8.1	E/ST		8.1	E/ST		5.6		
67-1				E/ST		9.3	E/ST		11.8	E/ST		16.2	E/ST		13.5		
68-1				E/ST		6.0	E/ST		10.3	E/ST		8.6	E/ST		4.9		
69-1				E/ST		13.8	E/ST		16.2	E/ST		16.2	E/ST		6.3		
70-1				E/ST		10.8	E/ST		11.3	E/ST		12.5	E/ST		14.9		
71-1				E/ST		19.7	E/ST		21.9	E/ST		27.9	E/ST		25.0		
72-1				E/ST		18.5	E/ST		23.6	E/ST		23.9	E/ST		16.7		
73-1				E/ST		6.3	E/ST		8.1	E/ST		8.8	E/ST		10.7		
74-1				E/ST		12.0	E/ST		14.0	E/ST		18.5	E/ST		14.2		

95-2	1/15	6.6	2/15	8.2	3/15	10.9	4/15	9.3	5/15	0.3	6/15	0.0	
96-2	1/15	10.6	2/15	16.2	3/15	19.7	4/15	18.0	5/15	9.8	6/15	0.0	
97-2	1/15	17.2	2/15	20.4	3/15	23.4	4/15	23.9	5/15	9.0	6/15	0.0	
98-2	1/15	7.9	2/15	10.9	3/15	12.2	4/15	13.9	5/15	0.7	6/15	0.0	
99-2	1/15	6.2	2/15	12.8	3/15	15.2	4/15	15.9	5/15	8.8	6/15	0.0	
0-2	1/15	7.4	2/15	11.6	3/15	13.9	4/15	11.3	5/15	0.0	6/15	0.0	
1-2	1/15	4.8	2/15	6.5	3/15	7.9	4/15	9.0	5/15	0.0	6/15	0.0	
2-2	1/15	5.2	2/15	7.3	3/15	9.8	4/15	6.5	5/15	0.0	6/15	0.0	
3-2	1/15	5.2	2/15	7.9	3/15	12.0	4/15	9.7	5/15	0.0	6/15	0.0	
4-2	1/15	8.5	2/15	10.3	3/15	12.5	4/15	5.0	5/15	0.2	6/15	0.0	
5-2	1/15	7.5	2/15	8.9	3/15	8.9	4/15	9.8	5/15	0.0	6/15	0.0	
6-2	1/15	8.9	2/15	11.8	3/15	14.2	4/15	12.3	5/15	0.0	6/15	0.0	
7-2	1/15	6.4	2/15	7.6	3/15	9.1	4/15	5.8	5/15	0.0	6/15	0.0	
8-2	1/15	5.2	2/15	9.5	3/15	10.2	4/15	12.6	5/15	3.4	6/15	0.0	
9-2	1/15	6.9	2/15	8.3	3/15	10.1	4/15	11.6	5/15	0.0	6/15	0.0	
10-2	1/15	2.6	2/15	4.3	3/15	4.6	4/15	6.5	5/15	0.0	6/15	0.0	
11-2	1/15	7.1	2/15	9.2	3/15	12.5	4/15	14.3	5/15	10.4	6/15	0.0	
□													
FIRST OF MONTH MEASUREMENTS													
average depth and swe :													
		5.6		9.2		12		14		9.5		0.1	
years		0	26	0	56	0	71	0	75	0	72	0	26
1971-2000 average :													
		6.7		9.8		12		15		10		0	
MID-MONTH MEASUREMENTS													
average depth and swe :													
		7.0		9.6		12.0		11.0		2.4		0.0	
years		0	26	0	26	0	26	0	26	0	26	0	26
1971-2000 average :													
		8.2		11.0		13.9		13.6		3.7		0.0	
NOTES: O/dd - October, J/dd - November, K/dd - December, E/ST - estimate Card type 1 = First of Month, 2 = Mid-Month, and 3 = Special Measurement /cdbbs/wy/snow56													

(a)

Monthly Mean Temperature (deg F) for Pinedale, Wyoming, site 487260												
YEAR	MONTH											
	1	2	3	4	5	6	7	8	9	10	11	12
1906	12.4	15.3	16.2	32.9	44.1	50.5	58.9	56.6	49.5	36.4	22.5	18
1907	10	18.2	23.5	33.7	42.7	50	59.1	54.8	48.8	41.3	25.9	14.5
1908	8.2	12.4	23	36.6	43.8	48.6	60.5	52.3	48.1	34.8	24.6	13.6
1909	14.1	12.4	19.8	28	39.9	.	.	.	.	.	.	.
1910	.	.	.	.	.	.	.	.	.	.	.	.
1911	.	.	.	.	.	.	.	.	.	.	.	.
1912	.	.	.	.	.	.	.	.	.	.	.	.
1913	.	.	.	.	.	.	.	.	.	.	.	.
1914	.	.	.	.	.	.	.	.	.	.	.	.
1915	.	.	.	.	.	.	.	.	.	.	.	.
1916	.	.	.	.	.	.	.	.	.	.	.	9.4
1917	5.1	13.2	17.8	28.2	41.8	50.6	.	.	50.1	37.7	31.4	21.9
1918	13.8	13.3	25.6	31.9	42.6	59.6	59.9	55.9	50.8	40.4	22.4	.
1919	15.5	13.4	22.3	.	48.1	57	.	58.8	.	31.2	20.1	9.3
1920	14.7	17	19	.	44.8	52.7	.	.	.	.	.	9.3
1921	.	15.5	.	.	.	.	.	.	.	.	.	.
1922	.	.	.	.	.	.	.	.	.	.	.	.
1923	.	.	.	.	.	.	.	.	.	.	.	.
1924	.	.	.	.	.	.	.	.	.	.	.	.
1925	.	.	.	.	.	.	.	.	.	.	.	.
1926	.	.	.	.	.	.	.	.	.	.	.	.
1927	.	.	.	.	.	.	.	.	.	.	.	.
1928	.	.	.	.	.	.	.	.	48.2	37.1	25.7	.
1929	7.6	7.8	21	29.4	42	49.7	60.6	59.1	45.1	37.7	23.2	20.7
1930	-1.9	20	21.5	39.9	42	50.3	60.1	57.4	46.5	34.6	24.5	17.8
1931	17.4	23.7	24.8	35.3	43.6	56.1	60.8	57.8	48.5	38.5	20.8	12
1932	6.1	14.5	19.5	.	.	.	57.4	53.7	49.3	35.7	27.2	4.2
1933	.	.	.	.	.	.	.	.	.	.	.	20.8
1934	17.1	26.2	32.9	.	.	.	.	.	.	.	.	.
1935	.	.	.	.	.	.	.	.	.	.	.	.
1936	.	.	.	.	.	.	.	.	.	.	.	.
1937	.	.	.	.	.	.	.	.	.	.	.	.
1938	.	.	.	.	.	.	.	.	.	.	.	.
1939	12.1	6.1	23.1	38	46.6	50	59.8	56.2	49	37.7	29.4	21.5
1940	11.4	18	26.1	35.8	49.1	58.8	61.1	58.7	51.2	39.3	20.3	14
1941	8.6	16.1	22.6	33	46.5	52.6	59.3	57.7	43.1	34.8	25.8	16.7
1942	6	4.9	15.7	34.2	40.3	49.3	59.8	56.7	49.8	38.3	26	14.5
1943	10.4	15.5	16.7	39.6	42.4	50.3	59.4	57.9	49.6	40	28.6	14.7
1944	9.5	13	19	32.6	45.1	50	58.2	55.3	48.4	40.3	23.7	14.3
1945	15.1	15.7	20.9	28.6	44	47	59.5	57.5	45.4	40.2	20.3	10.1
1946	7.6	12.2	24.5	38.4	41.3	53.6	61	59	47.6	33.4	21.9	20.4
1947	9.2	17.9	24.9	33.3	46.8	51.6	64.2	59.3	52.4	41.9	21.4	18
1948	15.5	16.7	20	34.4	45.3	55.5	59.5	57.2	52	38.7	19.5	8.5
1949	1.1	9	23.7	38.3	46.8	54	60.3	59.4	49.4	34.8	34	15.2
1950	9.5	14.6	20.9	32.2	40.2	50.9	57	54.8	47.6	41.3	22.3	18.8

1951	8	16.4	16.6	30.7	.	.	60.9	56.9	48.3	36.8	18.2	10
1952	6.5	10.1	13.5	28.9	40.5	55.6	60.3	58.2	.	.	13.4	10.7
1953	17.5	14.8	22.1	29.6	40.1	52.4	62	56.2	48.4	39	27.3	13.9
1954	15.3	.	.	.	.	.	.	.	48.2	38.6	30.7	15.2
1955	8.7	11.6	16	31.7	44.7	50.8	59.8	58.5	48.2	39.2	21.8	17.2
1956	12.2	6.3	18.6	.	.	54.4	58.7	54.5	.	.	.	.
1957	.	.	24	34.8	45.5	54.5	60.3	59.7	49.9	36.4	.	.
1958	.	.	.	.	.	55.1	57.4	59.7	49	39.1	25.8	17.3
1959	11.3	15.4	20.4	33.1	40.3	55.9	59.5	54.8	45.8	36.9	26.3	19.6
1960	10.5	9.8	23	35.2	42.4	52.1	59.7	54.2	49.9	36.8	21.7	.
1961	12.8	18.8	22.6	32.1	42.5	56	59.3	58.9	42.7	.	.	.
1962	.	.	.	.	45.1	51.5	56.2	54.1	47.8	40.5	28.5	20.9
1963	9.7	22.2	23.2	32.1	44.6	51.1	58.1	57.1	51.6	42.6	26.9	16.5
1964	9.3	9.5	16	31.6	42.8	49.3	60.6	53.3	46.2	38.7	22.2	12.1
1965	14.8	14.2	10.2	34	40.9	49.8	59.3	53.6	41	42.6	28.4	12.8
1966	8.2	9.4	20.1	31.8	46.1	50.1	61	55.7	50.7	.	27.7	13.1
1967	15.7	14.6	23.1	32.4	39.7	48.9	59.5	57.6	52.1	39	25.8	8.6
1968	9.8	16.9	23.9	29.1	40.6	51.7	58.1	54.1	46.7	36.6	20.4	10.8
1969	14.4	11.7	15.3	37.3	48.4	49.4	57.4	57.7	49.5	30.5	.	17.1
1970	14.6	19.2	21.5	28.2	42.8	53.2	58.9	58.5	.	32	23.6	11.2
1971	14.8	15.7	19.6	32.8	43.9	51.4	56.2	59.4	44.2	36.6	20.9	7.3
1972	10.3	15.2	26.7	34.6	44.6	54	57	56.9	45	37.5	22.2	9.1
1973	6.2	11.1	18.8	28.7	43.3	51.9	57.6	55.8	46.7	39.3	22.5	16
1974	7.6	14.5	26.3	35.4	43.8	54.6	59.7	53.8	46	39.5	26.4	15.1
1975	9.8	14.4	23.1	27.6	40.3	48.8	62.4	54.4	46.5	36.1	21.7	18.8
1976	13.5	15.5	16.6	33.5	46.9	51.2	59.8	54.5	49	36.6	27.7	19.5
1977	13.8	21.9	22.4	37	42.3	57.4	59.6	55	48.3	.	.	.
1978	.	.	.	.	42.1	52.4	59.3	54.3	47.2	38.8	19.2	5.5
1979	3	12.6	23.7	32.7	43.6	53	59	56.5	51	40.2	20	20.3
1980	11.4	18.6	21.8	34.1	44.2	52.2	59.1	53.6	48.7	38.7	25.4	24.8
1981	23.3	22.2	30.7	38.6	44	52.7	59.3	58.6	51.3	35.8	28.2	16.7
1982	11.5	12	23.4	28.8	42.1	51.6	58.7	60.1	48.2	35.8	20.6	13.4
1983	17	15.8	27.5	29.7	40.6	51.9	58	60.9	49	40.5	23.9	6.9
1984	12.1	13.9	23.3	30.4	43.4	51.2	61	58.5	44.5	31.1	21.4	8.1
1985	7.7	8.5	18.4	37.1	45.2	53.4	61.4	53.9	43.3	35.4	15.1	13.2
1986	13.1	18.1	27.7	35.2	43.6	57.1	56.4	56.8	43.6	37.8	22.4	11.7
1987	8.6	15.8	20.6	37.5	48.4	54.2	57.2	53.3	48.7	38.8	29.4	11.7
1988	8.8	16.1	24	37.1	43.9	57.8	60	54.9	45.6	41.5	20.1	11.2
1989	7.5	7.4	28	36.4	43	50.8	61	55.1	47.7	37.1	26.2	16.8
1990	12.8	12.2	26.2	38.1	40.9	53	59.4	57.5	52.4	36.1	23.7	2.6
1991	6.8	20.4	24.1	32.4	42.8	53.8	58.8	57.8	48.2	35.7	19.3	9.6
1992	11.3	20.2	32.1	39.3	47.9	53.8	55.3	56.7	46.4	38.5	19.5	5.5
1993	6.3	5.6	23	31.7	46	49.6	51.4	53.6	46.7	37	19.1	17.2
1994	18	15.9	29.3	36.4	48.3	55.1	59.6	58.9	49.9	36.5	20.7	17.3
1995	13.5	22.4	26.8	34.2	.	51.7	56.9	58.1	50.3	35.2	27.9	15.6
1996	11.3	15	22	34.6	43.6	54.5	60	56.7	46.6	.	26.9	14.3
1997	12.5	10.3	22.4	31.1	45.5	55.4	58.3	57.4	50.8	37.4	23.5	15.3
1998	14.5	15.6	20.7	34.4	44.5	47.9	62.2	58.1	52.6	37.7	26.3	15.7
1999	16.7	17	.	31.8	.	.	.	.	.	.	.	.

2000	.	.	.	.	.	53.1	61.3	.	46.3	.	14.5	13.2
2001	11.2	14.2	26.8	36.4	46.5	53.9	61.1	60.3	51.4	37.9	29.3	10.1
2002	9.7	.	20.8	36.5	43.2	53.6	62.5	55.9	.	.	.	.
2003	21.9	13.4	28.4	37.8	44.9	52.2	63.6	60.7	47.9	42.1	15.9	16.8
2004	9	12.9	27.6	38.7	43.5	.	59.6	55.1	47.3	38.5	25.7	18.9
2005	17.4	14.9	26.1	.	44.6	50.6	61.1	57.2	48.4	40.1	27.8	12.4
2006	14.1	11.3	20.9	38.3	45.6	55.5	63.1	56.5	47.3	36.8	23.6	15.2
2007	8.2	19.6	31.6	37.1	44.2	.	65	59.5	48.9	39.4	27.8	12.8
2008	5.9	14.1	20.1	29.1	42.1	52	60.4	57.9	47.3	38.1	31.2	14.6
2009	16.5	16.2	24.1	34.9	45	50.9	58.9	56.5	52.4	33.1	27.3	10.6
2010	14.3	15.5	29.4	34.9	38.5	52.5	59.2	57.1	50.1	41.6	.	17.6
2011	14.3	11.8	19.8	.	.	.	.	.	50.3	39.3	.	15.4
Source: MJ Menne CN Williams Jr. RS Vose NOAA National Climatic Data Center Asheville NC												
http://cdiac.ornl.gov/epubs/ndp/ushcn/access.html												

(b)

VITA

Jeffrey Allen Marks is currently a graduate student at The University of Tennessee. Upon graduating from The University of Tennessee with a Bachelor of Science in Civil Engineering spring 2011, he was immediately presented the opportunity to further his education by working towards a Master of Science in Environmental Engineering with a concentration in Water Resources working as a Graduate Research Assistant for Dr. Glenn Tootle at The University of Tennessee. During summer 2012, he was selected by his graduate advisor, Dr. Glenn Tootle, to be Dr. Tootle's teaching assistant for a study abroad course in Innsbruck, Austria. The three week study abroad program titled, "Climate and Climate Change Impacts in the European Alps," focused on glacier mass contributions to streamflow and the use of dendrochronology (tree rings) in water resources. Jeffrey has attended professional conferences in San Francisco, CA, Las Vegas, NV, and New Orleans, LA. He currently holds his Engineer in Training (EIT) Certificate and has plans to receive his Professional Engineering (PE) License in three years. Jeffrey's professional interests include the research, design, and implementation of environmental friendly solutions to the many water resource challenges that our world presents.