Estimates of Glacier Mass Loss and Contribution to Streamflow in the Wind River Range in Wyoming: Case Study

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Abstract: The Wind River Range is a continuous mountain range, approximately 160 km in length, in west-central Wyoming. 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; evaporation rates are high; and municipal, industrial, and irrigation water are at peak demands. Thus, the quantification of glacier meltwater (e.g., volume and mass) contributions to late summer/early fall streamflow is important, given that this resource is dwindling owing to glacier recession. The current research expands upon previous research efforts and identifies 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 by using empirically based volume–area scaling relationships. For 1966 to 2006, glacier mass contributions to JAS streamflow on the east slope were approximately 8%, whereas those on the west slope were approximately 2%. The volume–area scaling glacier mass estimates compared favorably with measured (stereo pair remote sensed data) estimates of glacier mass change for three glaciers (Teton, Middle Teton, and Teepe) in the nearby Teton Range and one glacier (Dinwoody) in the Wind River Range. **DOI: 10.1061/(ASCE)HE.1943-5584.0001050.** © *2014 American Society of Civil Engineers.*

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Introduction

The Wind River Range is a continuous mountain range, approximately 160 km in length, in west-central Wyoming (Fig. 1). The barrier (continental divide) serves as the dividing entity for three major river basins: Wind-Bighorn/Missouri/Mississippi, Green/Colorado, and 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 10 largest glaciers in the American Rocky Mountains (Bonney 1987). The east slope of the divide contains approximately 77% of the total glacier area, whereas the west slope contains the remaining area (Marston et al. 1991). Glaciers serve as valuable frozen freshwater reservoirs, storing water in the winter and releasing it during the warmer summer months (Marston et al. 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 nonglaciated watersheds (Ferguson 1973; Fountain and Tangborn 1985; Braithwaite and Olsen 1988). Glaciers also affect the annual hydrograph by delaying seasonal runoff through the 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 warm summer and fall months to supplement flows needed for irrigation, fisheries, and the fulfillment of interstate water compacts. All studies consulted for this research (Dyson 1952; Mears 1972; Meier 1951) indicate that the glaciers in the Wind River Range have been retreating since the 1850s, the approximate end of the Little Ice Age (Marston et al. 1991). Thus, the quantification of glacier meltwater (e.g., volume and mass) contributions to late summer/early fall streamflow is important, given that this resource is dwindling owing to glacier recession.

The earliest research on Wind River Range glaciers included Dinwoody Glacier and was published in 1931 (Wentworth and Delo 1931). Meier (1951) studied the glaciers around Gannett and Fremont Peak within the Wind River Range in 1950 and reported the surface area of Dinwoody Glacier to be approximately 3.47 km^2. In the 1980s, Thompson and Love (1987) evaluated Wind River Range glacier recession and trace metal concentrations. Later studies by Marston et al. (1989) and Wolken (2000) determined the area to be 2.91 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 that Dinwoody Glacier lost 0.064 km^3 of water equivalent between 1958 and 1983.

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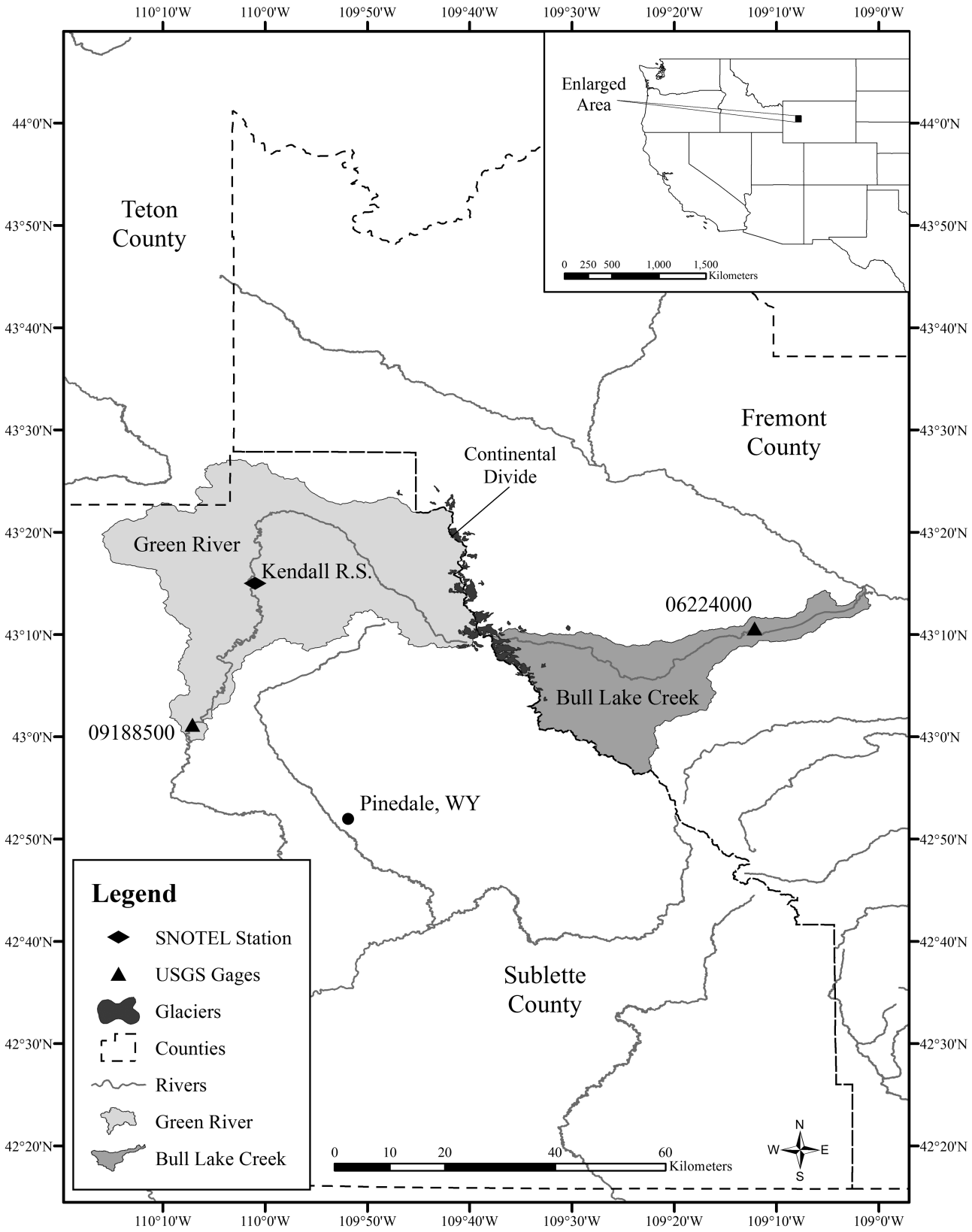

Fig. 1. Location map of watersheds (Bull Lake Creek and Green River), SNOTEL stations, and USGS streamflow gauges

Wolken (2000) updated the volume (mass) loss values by using aerial photography stereo pairs from 1983 to 1994, which determined that Dinwoody Glacier lost an additional 0.043 km^3 of volume (mass). Cheesbrough (2007) again updated these volume (mass) loss estimates for Dinwoody Glacier by using aerial photography and applying the stereo pairs methodology from 1983 to 2001, which determined the volume of Dinwoody Glacier to be 0.060 km^3. Cheesbrough et al. (2009) studied area changes for 42

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glaciers in the Wind River Range using Landsat imagery (30 m 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 m 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 nonglaciated watersheds in the Wind River Range and, using a paired watershed approach, examined how glaciers influence late summer/early fall (JAS) streamflow. Bell et al. (2012) determined that the influence of glaciers accounted for 23–54% of the JAS flow in glaciated watersheds. The majority of the increased flow was because the glaciers decelerated 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.

However, although Bell et al. (2012) estimated the influence of glaciers on JAS streamflow, no estimate was provided regarding how much JAS streamflow can be attributed to glacier volume (mass) loss. Thus, the objective of the current research is to estimate the percentage of volume (mass) contribution of glaciers to JAS streamflow. Two glaciated watersheds were identified, 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 was available from 1966 to 2006. Glacier 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 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 JAS streamflow was estimated for three periods: 1966–1989, 1989–2006, and 1966–2006, and the variability of the glacier mass contributions over these periods was explained through precipitation (snowpack) and temperature data sets.

Data

Streamflow from Glaciated Watersheds

An unimpaired stream gauge station is defined as a station with minimal effects of anthropogenic uses, including storage, diversion, and consumptive use. Unimpaired stations were identified by using the Hydro-Climatic Data Network (HCDN) (Slack et al. 1993; Wallis et al. 1991). USGS stream gauge information was obtained for all stream gauges in this study from the National Water Information System.

Although there are many gauges 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 gauge stations were evaluated to meet the previously stated criteria and two stations were selected: West Slope, USGS Station #09188500, Green River at Warren Bridge near Daniel, Wyoming (hereafter designated as Green River); and East Slope, USGS Station #06224000 Bull Lake Creek above Bull Lake, Wyoming (hereafter designated as Bull Lake Creek). The Green River watershed has a drainage area of 1,212 km^2 and the Bull Lake Creek watershed has a drainage area of 484 km^2. The majority of glacier melt and contribution to streamflow occurs during the late summer/early fall season (JAS) (Bell et al. 2012). Thus, this is the season of interest in the current research.

For the period of record of 1967–2006, the Green River gauge 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. The streamflow estimate of 93% was based on:

1. The climatic similarity established by Bell et al. (2012) between the Green River and Bull Lake Creek watersheds.
2. The correlation of yearly (1966–1992 and 1994–2006) Green River and Bull Lake Creek JAS (glacier meltwater season) streamflow, which was 0.95.
3. The 1992 JAS streamflow for Bull Lake Creek, which was 93% of the long-term average.

For each gauge, the average monthly discharge data in cubic feet per second (cfs) was converted to volume (m^3). This was accomplished by multiplying the monthly runoff in cfs as follows: $60\ s/min \times 60\ min/h \times 24\ h/day \times$ number of days in the month of interest $(30\ or\ 31) \times 0.0283\ m^3/ft^3$ (Table 1).

Glacier Area

Thompson et al. (2011) evaluated area change for 44 glaciers in the Wind River Range by using aerial photography (Table 2). Aerial photos were used owing to their extremely high resolution (approximately 1 m), 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.

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 between those in which the aerial photos were taken. For example, the 1966 aerial photo is assumed to have been taken after September 30, 1966, and the 1989 aerial photo was taken after September 30, 1989. Thus, the total JAS streamflow between the aerial photo dates is 1967 through 1989 (per Table 1). Similarly, the 1989 aerial photo is assumed to have been taken after September 30, 1989, and the 2006 aerial photo was taken after September 30, 2006. Thus, the total JAS streamflow between the aerial photo dates is 1990 through 2006 (per Table 1). The total JAS streamflow from 1966 to 2006 is the sum of these two, or the total JAS streamflow for 1967 through 2006 (per Table 1). Although 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 (Thompson et al. 2011) were identified (Fig. 2). For the Green River watershed, eight glaciers were identified; 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 km^2 in 1966, 1989, and 2006, respectively. For the Bull Lake Creek

Table 1. Total Streamflow in JAS

Watershed	1967–1989	1990–2006	1967–2006
Green River ($m^3 \times 10^6$)	3,689	2,237	5,926
Bull Lake Creek ($m^3 \times 10^6$)	2,625	1,702	4,327

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Table 2. Glacier Identifier, Watershed, Glacier Name, and Glacier Area with Error for 1966, 1989, and 2006

Glacier identifier	Watershed	Glacier names	Glacier surface area (km^2 or m^2 × 10^6)		
			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
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

Note: "NN" represents unnamed glaciers. Data from Thompson et al. (2011).

watershed, glacier area within the watershed was approximately 14.7, 11.9, and 8.0 km^2 in 1966, 1989, and 2006, respectively.

Methods

Several methods are available to estimate glacier volume (mass) based on glacier area (volume–area scaling relationships). Volume–area scaling relationships are most accurate when applied to glaciers that are in equilibrium with climate. Given that the Wind River Range glaciers are in recession, this may impact the estimate of glacier mass (as discussed later). These volume–area scaling methods determined that glacier volume (V, expressed in m^3) and area (A, expressed in km^2) are related by a power law, expressed as

$$V = \alpha A^{\beta} \tag{1}$$

Chen and Ohmura (1990) derived α and β by analyzing 63 glaciers having known areas and volumes by using topographic surveys and radio echo soundings in North America, Europe, and Asia. They derived α (0.120) and β (1.396) by using regression analysis on an area versus volume plot of the glaciers. Driedger and Kennard (1986) used similar methods to 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 that 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) 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:

- $\alpha = 32.7$ when area (A) is input as km^2 and the resulting volume (V) is in million m^3; and
- $\beta = 1.36$ for all variations based on the Bahr regression analysis plot (Bahr et al. 1997).

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 (mass) 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), the volume (mass) of each glacier in 1966, 1989, and 2006 can be estimated by using the Bahr equation (Bahr et al. 1997), and by subtracting the 2006 volume estimated from the 1966 volume estimate, the volume (mass) of glacier loss from 1966 to 2006 can be estimated. This is repeated for the periods of 1966 to 1989 and 1989 to 2006.

For example, to determine the volume loss for the single glacier (Mammoth Glacier) in the Green River watershed from 1966 to 2006, the volume of Mammoth Glacier in 1966 is first determined. For 1966, three volume calculations are performed by using the estimated average glacier area (2.959 km^2), the estimated maximum glacier area ($2.959 + 0.064 = 3.023$ km^2), and the estimated minimum glacier area ($2.959 - 0.064 = 2.895$ km^2). Using the equation of Bahr et al. (1997), this resulted in glacier volume (mass) estimates of 142.8, 147.1, and 138.7 m^3 × 10^6, respectively. For 2006, three volume calculations are performed by using the estimated average glacier area (2.028 km^2), the estimated maximum glacier area ($2.028 + 0.015 = 2.043$ km^2), and the estimated minimum glacier area ($2.028 - 0.015 = 2.013$ km^2). Using the equation of Bahr et al. (1997), this resulted in 85.5, 86.3, and 84.6 m^3 × 10^6, respectively (Table 3).

To determine the estimated volume loss (with error), three volumes were calculated. First, the 2006 average volume (85.5 m^3 × 10^6) was subtracted from the 1966 average volume (142.8 m^3 × 10^6), which resulted in 57.3 m^3 × 10^6. Next, the 2006 minimum volume (84.6 m^3 × 10^6) was subtracted from the 1966 maximum

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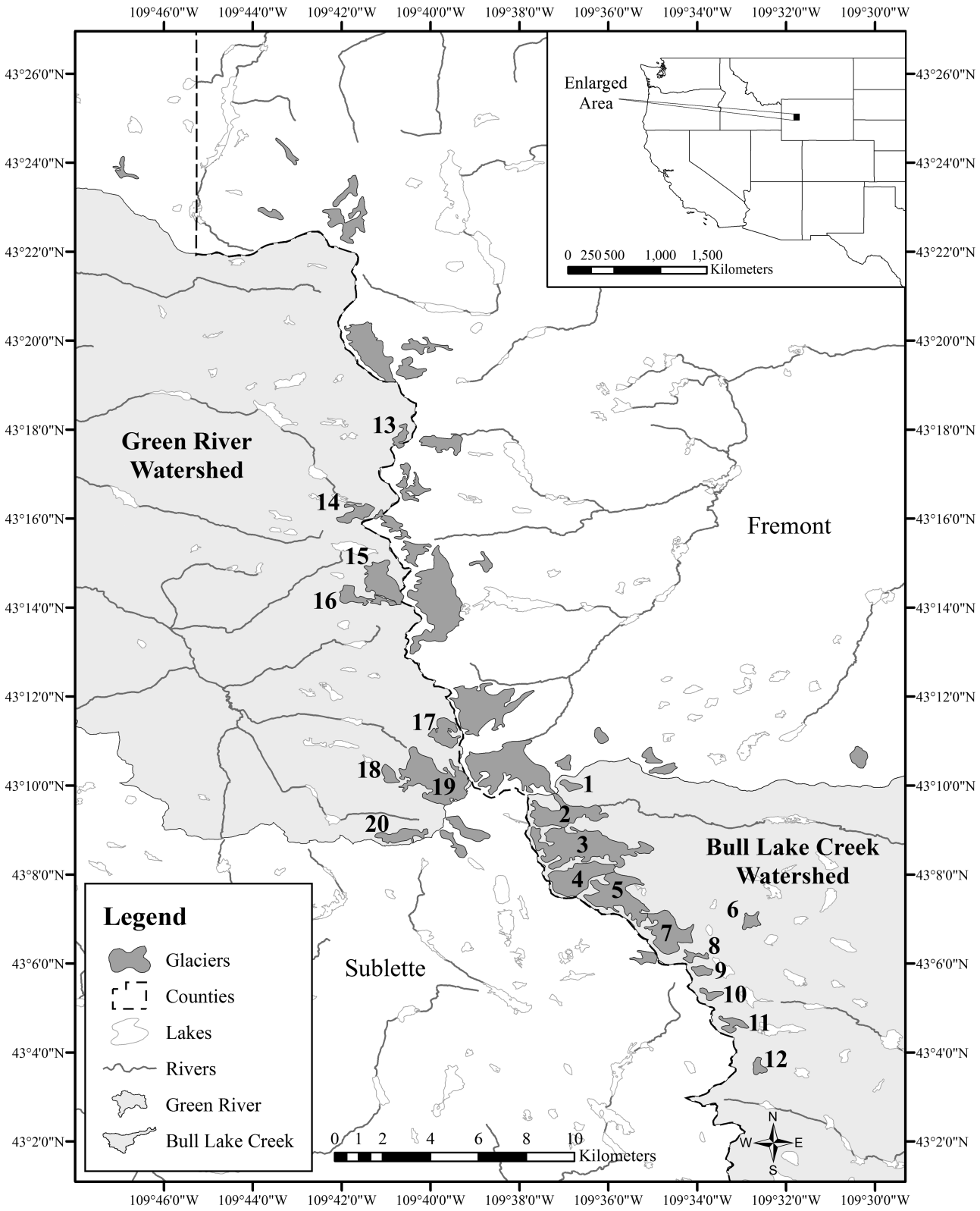

Fig. 2. Location map of 20 glaciers (identifiers provided) in the Wind River Range

volume (147.1 $m^3 \times 10^6$) which resulted in 63.1 $m^3 \times 10^6$. Finally, the 2006 maximum volume (86.3 $m^3 \times 10^6$) is subtracted from the 1966 minimum volume (138.7 $m^3 \times 10^6$), which resulted in 52.4 $m^3 \times 10^6$. Again, using Mammoth Glacier as an example, the estimated glacier volume (mass) loss ranged from 52.4 to 63.1 $m^3 \times 10^6$ with an average loss of 57.3 $m^3 \times 10^6$. 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). These values were divided by the total JAS streamflow (Table 1) for each watershed, for each period, to determine the percentage of glacier volume (mass) contributing to streamflow.

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Table 3. Glacier Identifier, Watershed, Glacier Name, and Average, Maximum, and Minimum Glacier Volume Estimates

Glacier identifier	Watershed	Glacier names	Average/maximum/minimum glacier volume ($m^3 \times 10^6$)		
			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
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

Note: "NN" represents unnamed glaciers. Estimates are per the Bahr et al. (1997) equation in $m^3 \times 10^6$.

Table 4. Basin, Average, Maximum, and Minimum Total Glacier Volume Estimates for 1966–1989, 1989–2006, and 1996–2006, and Percentage of JAS Streamflow

Basin	Average, maximum, or minimum	Estimated glacier volume ($m^3 \times 10^6$) and percentage of JAS streamflow		
		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. According 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. 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, or SWE) is collected (NRCS 2012). The Kendall Research Station (R.S.), located in the Green River

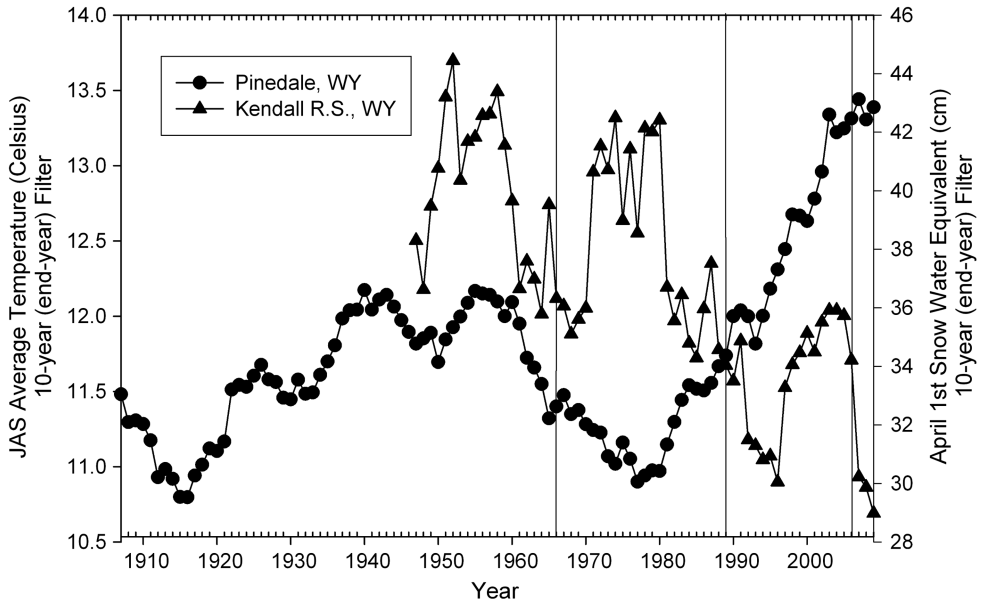

Fig. 3. April 1 SWE (cm) from the Kendall R.S. (Wyoming) SNOTEL station and JAS average temperatures (Celsius) from Pinedale (Wyoming): a 10-year filter was applied to each data set

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watershed (Fig. 1), was selected and has been utilized in previous research efforts (Aziz et al. 2010; Hunter et al. 2006). April 1 SWE, which typically represents the peak snowpack accumulation, was accessed and yearly values were plotted with a 10-year filter (10-year running average) (Fig. 3). The United States Historical Climatology Network (USHCN) is a high-quality data set of daily and monthly records of basic meteorological variables from 1,218 observing stations across the 48 contiguous United States (USHCN 2012; Easterling et al. 1996). Monthly data were accessed from Pinedale, Wyoming (Fig. 1) and yearly JAS average temperatures were calculated and plotted with a 10-year filter (10-year running average) (Fig. 3). The increased contribution of glacier volume (mass) from 1989 to 2006 is most likely associated with rapid JAS temperature increases and lower snowpack when compared to historical averages (Fig. 3). Edmunds et al. (2012) observed similar temperature and snowpack patterns in the Teton Range (Wyoming), located approximately 150 km from the Wind River Range. Previous research efforts (Naftz et al. 2002) in which ice cores were extracted from Freemont Glacier in the Wind River Range revealed rapid warming since the 1960s.

According to Table 4, glacier mass contributions to JAS streamflow were approximately 2% for the Green River watershed and 8% for the Bull Lake Creek watershed. 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 (Bahr et al. 1997). Obviously, this is not the case with Wind River Range glaciers because 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; it was estimated that these glaciers lost 3.2×10^6 m^3 ($\pm 0.46 \times 10^6$ m^3) from 1967 to 2002. Glacier area data (with error) were obtained for the three glaciers for 1967 and 2002. These data were input to the Bahr et al. (1997) equation to estimate glacier mass loss for comparison. According to the Bahr equation, these glaciers lost 2.8×10^6 m^3 ($\pm 0.43 \times 10^6$ m^3) from 1967 to 2002. Thus, the Bahr equation slightly (~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 60×10^6 m^3 of glacier mass was lost from 1983 to 2001. Using the Bahr et al. (1997) equation, it was estimated that 50×10^6 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 acceptable estimate of mass loss in Wind River Range glaciers, despite the current recession of the glaciers. However, future research efforts may focus on developing area–volume scaling relationships specific to Wind River Range glaciers. Although it is not feasible to perform radar echo soundings to determine the mass of Wind River Range glaciers, remote sensed products provide an historical data source such that three-dimensional surfaces of the glaciers can be created. Thus, area–volume loss relationships may be determined to assess mass loss.

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