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Article

Recent Alpine Glacier Variability: Wind River Range, Wyoming, USA

Abigail Maloof [1],*, Jesse Piburn [1], Glenn Tootle [2] and Greg Kerr [3]

[1] Oak Ridge National Laboratory, 1 Bethel Valley Rd, Oak Ridge, TN 37831, USA; E-Mail: piburnjo@ornl.gov

[2] Department of Civil, Construction and Environmental Engineering, University of Alabama, Tuscaloosa, AL 35487, USA; E-Mail: gatootle@eng.ua.edu

[3] Department of Civil and Architectural Engineering, University of Wyoming, 1000 East University Avenue, Laramie, WY 82070, USA; E-Mail: rrek@uwyo.edu

* Author to whom correspondence should be addressed; E-Mail: maloofar@ornl.gov; Tel.: +1-205-348-0662.

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Abstract: Glacier area and volume changes were quantified through the use of historical aerial photographs in the Wind River Range, Wyoming. Forty-four glaciers in the Wind River Range were analyzed using orthorectified aerial photography from 2012. This is an update to the work of Thompson *et al.* [1] in which the surface area changes of the 44 glaciers were estimated from 1966 to 2006. The total surface area of the glaciers was estimated to be 27.8 ± 0.8 km^2, a decrease of 39% from 1966 and a decrease of 2% from 2006. The 2012 volume changes for the 44 glaciers were estimated using the Bahr *et al.* [2] volume-area scaling technique. The total glacier volume in 2012 was calculated to be 1.01 ± 0.21 km^3, a decrease of 63% from 1966. These results, once compared to temperature and snowpack trends, suggest that the downward trend in snowpack as well as increasing temperatures seem to be the most likely driver of the glacier recessions. With Global Circulation Models (GCMs) forecasting higher temperatures and lower precipitation in the western U.S., it is likely that glaciers will continue to recede.

Keywords: glacier; remote sensing; climate; Geographic Information System (GIS); uncertainty

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1. Introduction

Glaciers cover approximately 10% of the earth's land surface and contribute to approximately 75% of the world's fresh water supply [3]. With recent studies finding that glaciers in the western United States have been losing mass since the Little Ice Age (1800s), the west has seen large variation in summer streamflows [4,5]. Streamflow in the west is a major source for municipal, agricultural, and hydropower use. Hence, there is a renewed interest concerned with assessing glacier surface area changes due to climate warming [1].

Glaciers serve as natural frozen reservoirs that release water during the late summer months. The storage and release of water from glaciers is important for hydroelectric power, accurate flood forecasting, sea level fluctuations, glacier dynamics, sediment transport, and formation of landforms [6]. With 70% of the water supply for the west coming from snow and glacier melt, analysis of both has important implications for the management of streamflow [7–9]. The Wind River Range is a 160-km barrier in west central Wyoming that is host to 63 glaciers [10]. The snow and glacial meltwater from the Wind River Range provides crop irrigation and fisheries for hunting and fishing for the Wind River Indian Reservation, located directly to the east of the range [11]. Meier [12] estimated that approximately 132×10^6 m^3 of the total July-August streamflow was derived from glaciers in Wyoming. This amounts to approximately 13% of the average combined flow for July and August from the Green River, Clarks Fork of the Yellowstone River, and the Big Horn River which are the rivers receiving the majority of the Wyoming glacier runoff [12].

Remote sensing is a useful and often efficient way to study glacier areas [13]. The availability of imagery data for otherwise inaccessible areas makes it a common tool when monitoring glacier changes over a large area. Cheesbrough *et al.* [5] used 30-m resolution Landsat imagery to study area changes of 42 glaciers in the Wind River Range from 1985 to 2005. Thompson *et al.* [1] expanded on that research and examined 44 glaciers in the Wind River Range from 1966 to 2006 using 1-m resolution aerial photography. The objectives of this study are to use methods presented in Thompson *et al.* [1] to detect surface-area changes for 44 glaciers in the Wind River Range between 2006 and 2012 and estimate volume changes for the 44 glaciers between 1966 and 2012.

2. Data and Methods

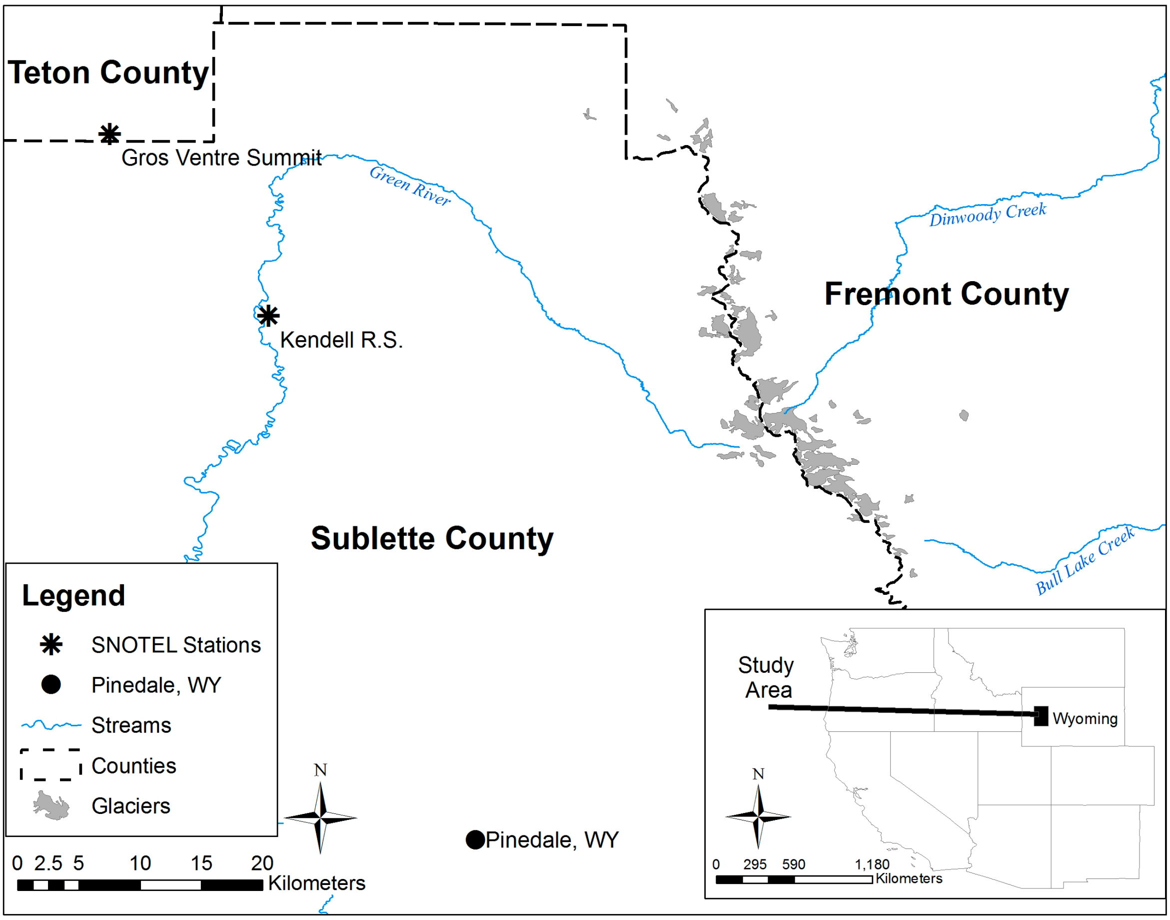
2.1. Study Area

The Wind River Range is the largest discrete mountain mass in Wyoming with nearly 160 km of unbroken mountain range [10]. With 63 glaciers, it contains 7 of the 10 largest glaciers in the American Rocky Mountains [14]. The majority of these glaciers are found in the northern portion of the range along the Continental Divide in Fremont and Sublette Counties (Figure 1a) [15]. The glaciers are thought to be remnants from the Little Ice Age, a period that occurred between 1400 and the 1800s [14,16], but Thompson and Love [17] cited evidence that glaciers may date back as far as 3000 years ago. Several authors [15,18,19] have noted that glaciers of the Wind River Range have been receding since the end of the Little Ice Age (1850). Dyson [19] reported that glaciers in the range were retreating at a rate of 7% to 41% per year.

The glaciers are located within a minimum and maximum elevation of 3113–4205 m [20]. The Continental Divide runs through the highest elevations of the Wind River Range and acts as a boundary between Sublette and Fremont Counties in Wyoming [1]. Runoff on the eastern slopes flows into the Missouri River Basin and then into the Gulf of Mexico whereas runoff from the western slopes flows into the Colorado River Basin and then into the Gulf of California. The runoff from the glaciers in the Wind River Range is considered vital to the west, especially during the summer months and years with low precipitation [21].

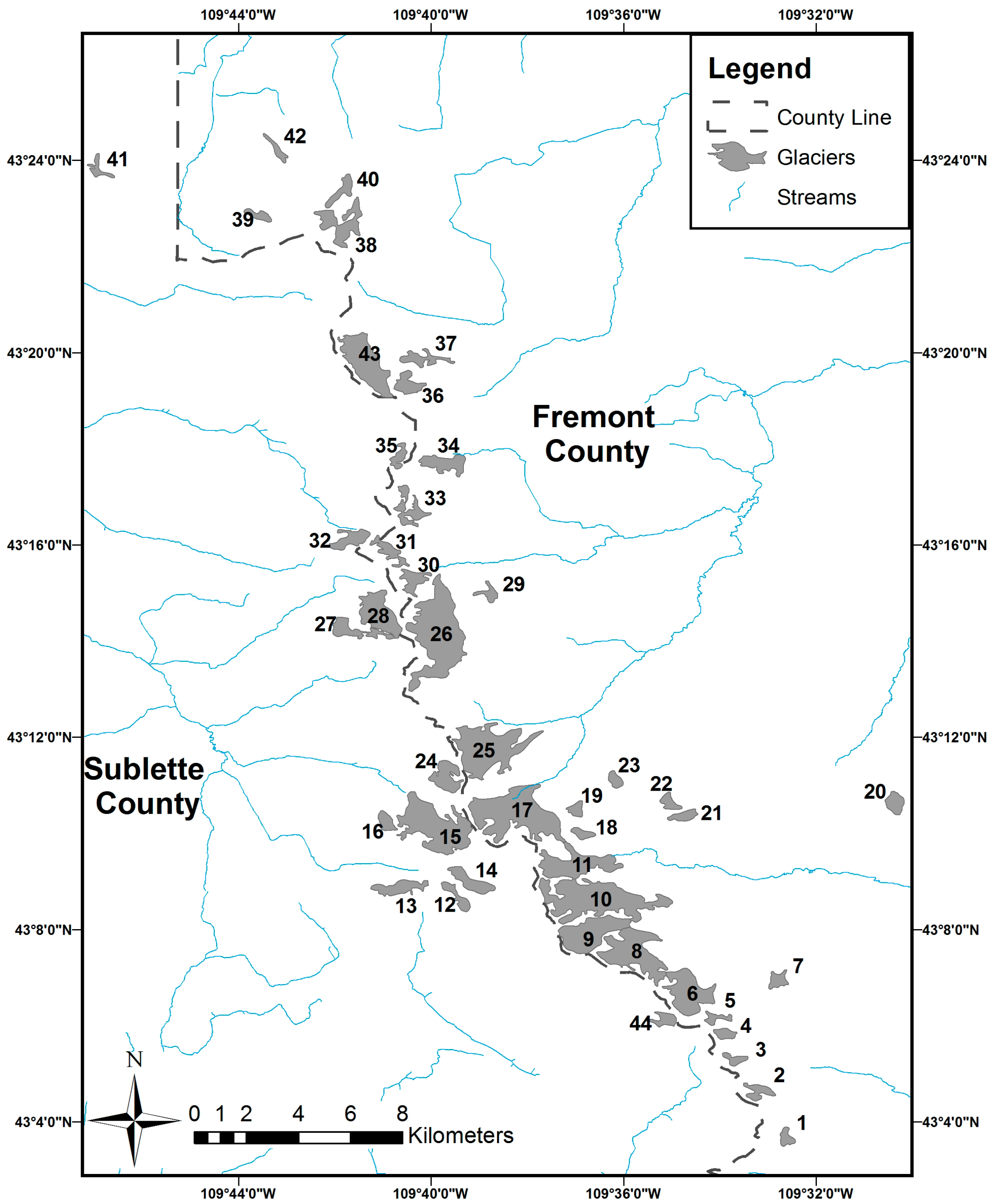
From 1971 to 2000, the average annual precipitation at the higher elevations of the Fremont Peak area of the Wind River Range was 1143 mm/year [22]. The precipitation usually falls as snow in the winter months as a result of Pacific air masses lifting over the mountains, with the southwestern (windward) flanks receiving more precipitation than the northeastern (leeward) flanks [23]. Approximately two thirds of the precipitation runs off as streamflow [24].

Figure 1. (**a**) Study area of Wind River Range, Wyoming, USA and SNOwpack TELemetry (SNOTEL) Station Sites. (**b**) Location map of 44 glaciers in the Wind River Range.



(**a**)

Figure 1. *Cont.*



(b)

2.2. Data

For this study, 1-m resolution aerial photography was used to examine area changes between 2006 and 2012 for the 44 glaciers analyzed in Thompson *et al.* (Figure 1b) [1]. Imagery was obtained from the Wyoming Geographic Information Science Center (WyGISC) in Laramie, Wyoming for 2006 and 2012. Images from WyGISC were in the form of orthorectified mosaic and taken in the late summer months when snowcover is minimal. Each photo was digitized and georeferenced by WyGISC to the

Universal Transverse Mercator (UTM) zone 12 North coordinate system using the North American Datum 1983 (NAD83).

2.3. Methods

The methods implemented by Thompson *et al.* [1] for examining glacier surface-area changes were implemented in this study. Thompson *et al.* [1] used aerial photography to detect surface area and volume changes for a set of glaciers located in the Wind River Range between the years of 1966, 1989, and 2006. Volume changes were then calculated to determine the amount of glacier meltwater contributing to streamflow for the 41 year period. Thompson *et al.* also examined trends for ten glaciers using resampled (simulated data in other spatial resolutions) aerial photograph at resolutions of 10, 15, 22.5 and 30 m for 1966 and 2006 images to assess the relationship between area and measured scale. They found that the courser the resolution of the image became, the more it underestimated the total glacier area [1].

For this study, a primary network of 44 glaciers were selected in the Wind River Range to represent a good subset of glaciers, as they vary in size, elevation, and aspect [25]. The remaining 19 glaciers in the Wind River Range were not examined due to lack of historical area data. A Geographic Information System (GIS) was used to examine the remotely sensed images and study area changes. Many methods exist for analyzing glaciers. Using aerial photography to detect changes in a feature is considered time-consuming and cumbersome [26]. However, photo interpretation provides the most accurate classification (90% or higher) of temporal landscape changes [26,27].

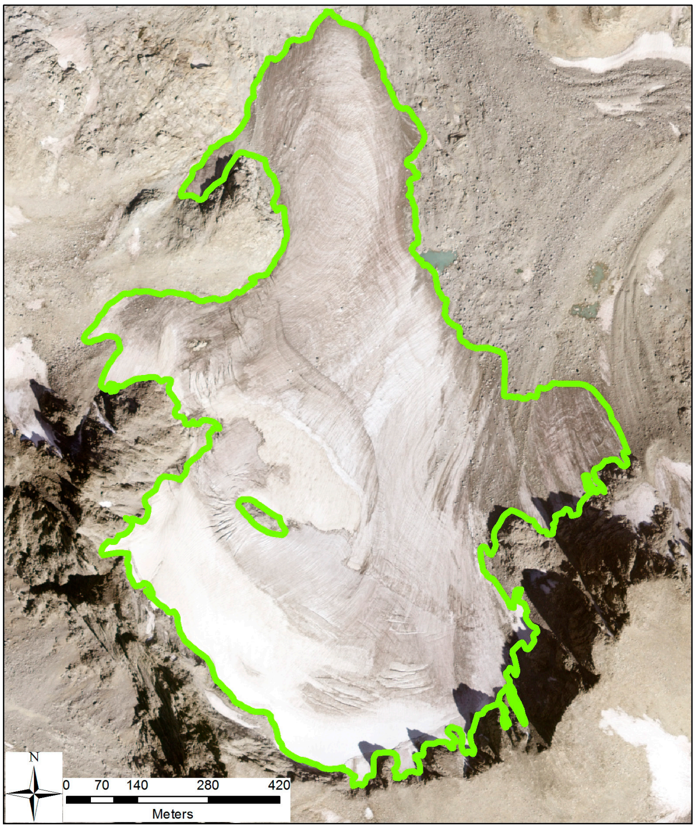
The digitized and georeferenced images were imported into ArcGIS 10.0 [28] and the glacier boundaries were manually interpreted. All photos were interpreted by the same analyst in order to minimize interpretation errors between years. A problem in identifying the glacier boundaries is that it is nearly impossible to detect every mass of snow and ice that fits a glacier definition [16]. Glacier boundaries were analyzed on the basis of recognition elements (*i.e.*, shape, size, pattern) described by Avery and Berlin [29]. Glaciers were identified and digitized based on their glacial ice boundaries, ice extents, and stagnant ice (ice physically separated from main glacier body). Digitization in ArcGIS involved creating a new polygon shapefile for each glacier being analyzed. Each individual shapefile was then edited in ArcGIS to incorporate the glacier boundary as shown in Figure 2. An area field was added to the attributes table of each shapefile and the *Geometry Calculator* was used to calculate the area of the glacier. This method was repeated for each glacier in 2006 and 2012.

Using methods presented by Bahr *et al.* [2], glacial ice volumes can be estimated from known quantities such as surface area. The Bahr *et al.* [2] method is based on the width, slope, side drag, and mass balance of 144 glaciers in Europe, North America, Central Asia and the Arctic. Bahr *et al.* [2] tested the parameters against the known volumes (calculated with radio echo soundings) and the areas of each individual glacier. They determined that glacier volumes (m^3) and areas (m^2) could be related by a power law expressed as:

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

where α and β are empirically derived constants equal to 0.226 and 1.36 when calculated from the Bahr *et al.* [2] regression analysis plot.

Figure 2. Delineation of Knife Point Glacier for 2006.



Temperature data were accessed from the United States Historical Climatological Network for Pinedale, Wyoming (Figure 1a). Monthly average temperatures for the months of July, August, September (JAS) were then averaged to determine a seasonal (JAS) average. The JAS period is commonly recognized as the season of peak glacier melt. Three periods were evaluated, 1967 to 1989, 1990 to 2006, and 2007 to 2012. Given that aerial photographs were taken in the late summer/early fall, the 1967 to 1989 period would correspond to glacier change for aerial photographs obtained in 1966 and 1989. The 1990 to 2006 period would correspond to glacier change for aerial photographs obtained in 1989 and 2006. The 2007 to 2012 period would correspond to glacier change for aerial photographs obtained in 2006 and 2012.

Snowpack (Snow Water Equivalent—SWE) data were accessed from the United States Department of Agriculture, Natural Resources Conservation Service, National Water and Climate Center. The 1 April SWE is typically the maximum (peak) snowpack and data were obtained for two SNOTEL (SNOwpack TELemetry) sites, Gros Ventre Summit and Kendall R.S. (Figure 1a). Yearly April 1st SWE for each SNOTEL site were averaged for the same periods (1967 to 1989, 1990 to 2006, and 2007 to 2012) as selected for the temperature evaluation.

2.4. Uncertainty

2.4.1. Area Error Estimation

Shadows along glacier edges, debris, and rock outcroppings create challenges when determining glacier boundaries. In most cases, it is nearly impossible to distinguish the exact outline of the glacier.

Debeer and Sharp [30] proposed a technique in which repeated measurements of the surface-area are made for each glacier over the study area. Repeated measurements take into account the errors associated with both manual delineation as well as glacier boundary interpretation. Glacier boundaries were delineated a minimum of 3 times to determine both minimum and maximum area changes and to identify any omitted or incorrectly identified glacial areas. The overall uncertainty of each glacier's surface area change was estimated based on the differences in area change as a result of multiple interpreter boundary delineations.

2.4.2. Volume Error Estimation

Glacier volume and volume change estimates are subject to uncertainty due to the error in the area measurements [30]. To estimate this uncertainty, the average difference between volume estimates using Chen and Ohmura [31] and Driedger and Kennard [32] methods were taken as a measure of the error for the volume calculated using the methods in Bahr *et al.* [2].

3. Results

Using aerial photography, Thompson *et al.* [1] calculated a total surface area of 45.9 ± 1.6 km^2 in 1966 for 44 glaciers in the Wind River Range. The glaciers less than 0.5 km^2 accounted for 50% (22 glaciers) of the glacier population. Using the same methods for 2012, this study calculated a total surface area of 27.8 ± 0.8 km^2, a reduction of 18.1 ± 0.8 km^2 (39%) from 1966. The glaciers less than 0.5 km^2 in 2012 accounted for 70% (31 glaciers) of the glacier population. A total glacier loss of 0.7 ± 0.4 km^2 (2%) was calculated between 2006 and 2012 (Table 1).

Using Bahr *et al.*'s [2] methods for volume estimation, a total ice volume of 1.01 ± 0.21 km^3 was calculated for 2012. This estimate represents a first-order estimate since field work to measure glacier volumes for each glacier was not feasible. From results found in Thompson *et al.* [1], the total volume decrease from 1966 to 2012 was 63% (0.928 ± 0.11 km^3). The 44 glaciers receded 4% from 2006 to 2012 (Table 1).

The average JAS temperature for the 1967 to 1989 period was 13.2 °C (55.7 °F); for the 1990 to 2006 period was 13.2 °C (55.8 °F); for the 2007 to 2012 period was 13.6 °C (56.5 °F). Thus, while JAS temperatures were relatively unchanged for the period of study (1966 to 2006) there was a slight increase in JAS temperatures for the period (2008 to 2012) of the current study. The average yearly JAS temperatures were also averaged for the period of 1902 to 1966 (prior to the studies). The average JAS temperature for this period was 13.7 °C (56.6 °F). Thus, JAS temperatures were relatively constant over the past ~110 years.

For both SNOTEL sites, snowpack continually declined in each period. The April 1st SWE for Gros Ventre Summit (Kendall R.S.) for 1967 to 1989 was 36.8 cm/14.5 in. (37.6 cm/14.8 in.), for 1990 to 2006 was 33.3 cm/13.1 in. (32.5 cm/12.8 in.), and for 2007 to 2012 was 29.2 cm/11.5 in. (27.4 cm/10.8 in.). April 1st SWE was investigated for each site. For the Gros Ventre Summit site, the average April 1st SWE for 1948 to 1966 was 40.4 cm/15.9 in. while the average April 1st SWE for the Kendall R.S. site for 1938 to 1966 was 38.9 cm/15.3 in. Thus, snowpack in this region has been in steady decline during the period of study (1966 to 2006) and for the period (2008 to 2012) of the current study.

Table 1. Glacier surface areas (km^2) and volumes (km^3) in the Wind River Range (2006 and 2012).

Glacier ID	Glacier Name	Glacier Surface Area (km^2)			Glacier Volume (km^3)
		2006 Thompson *et al.* [1]	2006	2012	2012
1	NN	0.095 ± 0.001	0.095 ± 0.000	0.087 ± 0.003	0.001 ± 0.0003
2	NN	0.176 ± 0.007	0.178 ± 0.003	0.171 ± 0.003	0.003 ± 0.0004
3	NN	0.177 ± 0.004	0.178 ± 0.006	0.171 ± 0.006	0.003 ± 0.0004
4	NN	0.181 ± 0.003	0.183 ± 0.001	0.174 ± 0.005	0.003 ± 0.0004
5	NN	0.142 ± 0.004	0.142 ± 0.009	0.139 ± 0.001	0.002 ± 0.0004
6	Knife Point	0.79 ± 0.004	0.789 ± 0.003	0.714 ± 0.025	0.021 ± 0.0020
7	NN	0.174 ± 0.005	0.175 ± 0.005	0.164 ± 0.002	0.003 ± 0.0004
8	Bull Lake	1.716 ± 0.051	1.707 ± 0.002	1.637 ± 0.020	0.064 ± 0.0133
9	Upper Fremont	1.306 ± 0.006	1.292 ± 0.004	1.294 ± 0.001	0.046 ± 0.0083
10	Sacagawea	2.046± 0.030	2.039 ± 0.004	1.898 ± 0.008	0.078 ± 0.0177
11	Helen	1.075 ± 0.046	1.067 ± 0.010	1.048 ± 0.037	0.035 ± 0.0052
12	NN	0.142 ± 0.003	0.142 ± 0.006	0.131 ± 0.018	0.002 ± 0.0004
13	Stroud	0.409 ± 0.007	0.407 ± 0.004	0.403 ± 0.004	0.010 ± 0.0001
14	Twins	0.385 ± 0.009	0.371 ± 0.024	0.340 ± 0.001	0.008 ± 0.0001
15	Mammoth	2.028 ± 0.015	2.028 ± 0.023	1.990 ± 0.072	0.083 ± 0.0193
16	Baby	0.221 ± 0.004	0.221 ± 0.001	0.201 ± 0.002	0.004 ± 0.0004
17	Dinwoody	2.474 ± 0.054	2.478 ± 0.027	2.312 ± 0.034	0.102 ± 0.0254
18	NN	0.147 ± 0.003	0.146 ± 0.002	0.142 ± 0.001	0.002 ± 0.0004
19	Heap Steep	0.109 ± 0.002	0.109 ± 0.002	0.102 ± 0.003	0.001 ± 0.0004
20	NN	0.286 ± 0.005	0.288 ± 0.006	0.281 ± 0.006	0.006 ± 0.0003
21	NN	0.133 ± 0.010	0.133 ± 0.005	0.123 ± 0.001	0.002 ± 0.0004
22	NN	0.0986 ± 0.001	0.099 ± 0.004	0.093 ± 0.002	0.001 ± 0.0003
23	NN	0.159 ± 0.003	0.157 ± 0.002	0.153 ± 0.005	0.003 ± 0.0004
24	Minor	0.425 ± 0.004	0.425 ± 0.011	0.412 ± 0.008	0.010 ± 0.0002
25	Gannett	3.27 ± 0.025	3.282 ± 0.045	3.245 ± 0.034	0.162 ± 0.0464
26	Grasshopper	2.48 ± 0.026	2.465 ± 0.014	2.453 ± 0.034	0.111 ± 0.0283
27	J	0.344 ± 0.004	0.345 ± 0.004	0.331 ± 0.004	0.007 ± 0.0001
28	Sourdough	0.922 ± 0.001	0.923 ± 0.006	0.895 ± 0.030	0.028 ± 0.0036
29	NN	0.087 ± 0.003	0.086 ± 0.003	0.088 ± 0.009	0.001 ± 0.0003
30	NN	0.286 ± 0.005	0.281 ± 0.017	0.274 ± 0.012	0.006 ± 0.0003
31	NN	0.275 ± 0.016	0.297 ± 0.007	0.324 ± 0.012	0.007 ± 0.0002
32	Connie	0.332 ± 0.003	0.332 ± 0.000	0.303 ± 0.022	0.006 ± 0.0002
33	NN	0.442 ± 0.003	0.434 ± 0.003	0.468 ± 0.051	0.012 ± 0.0004
34	Downs	0.518 ± 0.003	0.516 ± 0.011	0.516 ± 0.009	0.013 ± 0.0007
35	NN	0.127 ± 0.004	0.128 ± 0.005	0.125 ± 0.022	0.002 ± 0.0004
36	NN	0.770 ± 0.011	0.770 ± 0.006	0.685 ± 0.078	0.020 ± 0.0018
37	NN	0.246 ± 0.000	0.244 ± 0.007	0.242 ± 0.034	0.005 ± 0.0003
38	NN	0.389 ± 0.008	0.387 ± 0.006	0.368 ± 0.048	0.008 ± 0.0000
39	NN	0.146 ± 0.000	0.144 ± 0.004	0.145 ± 0.014	0.002 ± 0.0004
40	NN	0.010 ± 0.000	0.098 ± 0.003	0.115 ± 0.014	0.002 ± 0.0004
41	NN	0.051 ± 0.001	0.053 ± 0.001	0.131 ± 0.004	0.002 ± 0.0004
42	NN	0.039 ± 0.001	0.038 ± 0.001	0.062 ± 0.001	0.001 ± 0.0003
43	Continental	2.671 ± 0.009	2.648 ± 0.008	2.661 ± 0.032	0.124 ± 0.0328
44	Harrower	0.141 ± 0.002	0.145 ± 0.004	0.160 ± 0.004	0.003 ± 0.0004

4. Conclusion

This study investigated the area and volume changes from 2006 to 2012 of 44 glaciers in the Wind River Range, Wyoming. Glacier extents were delineated using historical aerial photographs and the methods presented in Thompson *et al.* [1]. With glacier melt contributing to streamflow in the Western United States, its analysis has important implications for the future management of water in the west. While glaciers in the Wind River Range decreased approximately 2% in surface area and 4% in volume from 2006 to 2012, glacier area and volume changes are highly variable in the United States. Marston *et al.* [14] examined Dinwoody Glacier from 1958 to 1983 and found an aerial reduction of 15.4%. They predicted Dinwoody Glacier would disappear by 2010. With a 2012 surface area of 2.312 km^2, Dinwoody Glacier has only decrease by 32% in the last 54 years. Based on this data, it seems that glacier recessions have slowed down.

While glacier aspect (solar radiation) and avalanche will impact glacier recession or growth, temperature and precipitation (snowpack) are the primary climatic drivers of alpine glacier variability. It appears the downward trend in snowpack is the most likely driver of the glacier recession (area loss) observed in the previous and current research efforts. Mote *et al.* [33] observed a similar trend of declining snowpack in the western U.S. from 1950 to 1997, including the current study region. Thus, if Global Circulation Models (GCMs) continue to forecast higher temperatures and lower precipitation in the western U.S., alpine glaciers are likely to continue in a period of recession.

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Author Contributions

Abigail Maloof wrote the introduction and data and methods section and contributed to the abstract, results, and conclusion. Jesse Piburn added major input and revisions throughout the data and methods section. Glenn Tootle contributed to the abstract and provided the data and research for temperature and snowpack. Greg Kerr contributed to the conclusion and added significant expertise in the field of glacier recession.

Conflicts of Interest

The authors declare no conflict of interest.

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