TOPOGRAPHICAL MASS BALANCE DETERMINATION OF TETON GLACIER, WYOMING

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ABSTRACT

The presence of glaciers affects stream discharge because they store precipitation and influence the timing of runoff. A glacier's influence is attributed at least in part to its change in mass. Mass balance, a calculation of the glacier's change in mass over a period of time, has been estimated in this study by volumetric changes assessed from surface fluctuations assuming constant density. Our analysis used topographic surveys performed in 1954, 1963, and 1994 of Teton Glacier, Wyoming. The surveys were used to create representative surfaces that were quantitatively compared using geographic information system (GIS) tools. Calculations performed indicate an average decrease of 26,000 $m^3\ yr^{-1}$ from 1954 to 1994.

INTRODUCTION

Basin hydrology can be influenced by the presence of glaciers in the basin (Meier, 1969; Post et al., 1971; Tangborn, 1968). The extent of a glacier's influence on the timing and amount of runoff is attributed at least in part to its size, which is a result of climatic and geographic conditions. The analysis of the glacier's change in size can be determined by using a mass balance approach. A negative mass balance usually indicates the retreat or the down-wasting of a glacier. A positive mass balance indicates that the glacier has accumulated mass over a period. The ability of the glacier to retain water and thus increase the lagtime between runoff from unglaciated portions of the basin and that of the glaciated area is reduced with a loss of mass. The ability to account for the change in a glacier's mass and thus the influence on basin hydrology may provide water resource managers with better decision support for greater optimization of the resource. The use of modern techniques may allow for increased mapping accuracy, more timely glacier calculations, and less expense.

It is essential to have reliable hydrologic data to accurately forecast, design and optimize water resources. A glacier's contribution to basin discharge must be accounted for to accurately predict discharge from glacierized basins (Østrem, 1986). Runoff is influenced by the storage remaining from the past winter that produces an annual total runoff that may be greater or less than the annual basin precipitation (Young, 1985). One method of accounting for a glacier's contribution to basin discharge is to perform annual mass-balance measurements (Østrem, 1986). Pochop et al., (1989) determined that Gannett and Dinwoody Glaciers located in the Wind River Mountain range of Wyoming contributed approximately 27 percent of the September flows and 32 percent of the October flows to Dinwoody Creek. Their study also indicated rapid declines in the mass balance of the glaciers, with an estimation of complete ice loss in the near future. The consequence of reduced glacier contribution to summer water supplies as a result of shrinking glaciers will be the increased effort to meet all water requirements from local irrigation to interstate water compacts with limited water resources (Pochop et al, 1989).

There are three kinds of mass balance methods available to identify a glacier's runoff contribution: glaciological, hydrological and topographical. The glaciological approach is the traditional method described by Østrem and Brugman (1991) and involves the recording of the changes in glacier mass by measuring the change of position and elevation of ablation stakes placed in the glacier surface and the measurement of glacier density taken from snow pits. This method has proven to be time consuming and is limited to a small number of glaciers by physical resources. Mass balances are calculated for a hydrological year based upon a fixed date or from the end of ablation season.

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The hydrological mass balance determines the change in glacier mass from an accounting of basin precipitation and basin discharge (Tangborn, 1966). This method has been shown to be ineffective because of the unknown amounts of water stored internally in the glacier, which can be released during the year resulting in errors (Tangborn et al., 1975).

The topographical method involves the use of digital elevation models (DEMs) to represent glacial surfaces from different periods. Each surface is generated from spatial information (x, y, z) portraying the surface. Topographic surveys, aerial photographs and other remotely sensed data can be used to generate the necessary spatial requirements. Additionally, each surface point must be properly geo-referenced to the same point on the succeeding surface. Properly referenced surfaces are compared and the change determined. The change in volume represents the net volumetric change for the glacier (Young and Ommanney, 1984), assuming that the density of the glacier remains the same. This difference can be assumed to be the glacier's contribution to the basin discharge (Østrem, 1986). The topographic method was used in this study to produce volume calculations.

Three surveys of Teton Glacier were used in the topographical mass balance approach to estimate the change in the glacier's mass between years of observation. This approach defines the annual mass-balance as the change in the volume of ice between two occasions (Haakensen, 1986). The method compares the changes in elevation of the representative glacier surfaces for each of the surveys. A similar method of subtracting representative surfaces from 1958 and 1983 was used for Dinwoody and Gannett Glaciers in the Wind River Range, Wyoming (Pochop et al., 1989). The work relied upon the Theissen polygon weighted-average method to calculate a weighted average depth change for the total glacier area from vertical measurements using a stereo zoom transfer scope fitted with a vertical measurement module (ZTS/VM) to analyze stereo-pairs of aerial photographs (Pochop et al., 1989). Results of ice loss from Dinwoody and Gannett Glaciers were 1.4 m yr^{-1} (59,829 acre-feet) and 1.7 m yr^{-1} (64,881 acre-feet) respectively (Pochop et al., 1989).

DESCRIPTION OF STUDY AREA

Teton Glacier is an easterly facing cirque glacier occupying approximately 300,000 m^2 (30 ha) in Grand Teton National Park, Wyoming centered at 43°44' 30"N and 110° 47' 0"W (Figure 1). The glacier lies at the head of an alpine valley within the Teton Range between the steep walls of the east ridge of Grand Teton (4196 m) to the south and Mount Owen (3937 m) to the north. Elevation of the glacier ranges from 3095 m to 3500 m a.s.l.

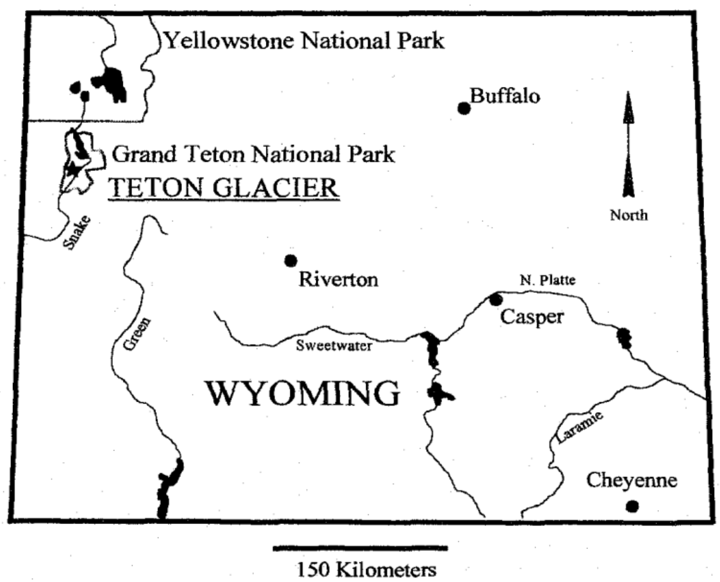

Figure 1 - Project Site Location

The lower portion of the glacier is covered by rock debris. The upper portion of the glacier is characterized by steep terrain, a 30 to 40 m icefall, and small rock debris on the surface (Figure 2).

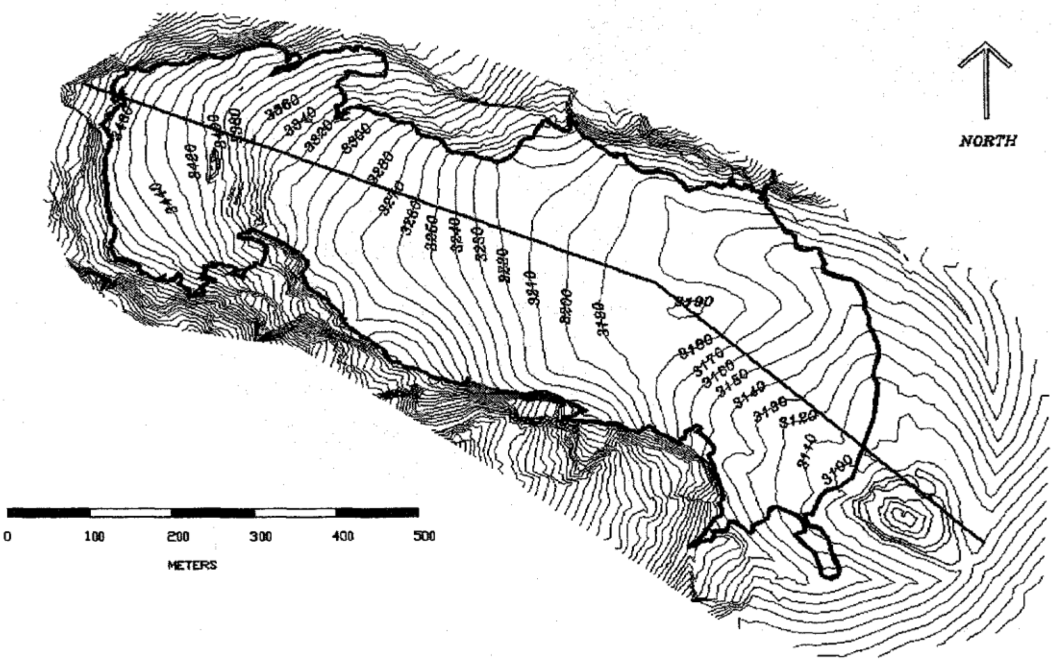

Figure 2 – 1996 topographic map of Teton Glacier and surrounding area. Glacier margin is indicated by heavy dark line. Elevation contours are 10 meter intervals. Transect established by Reed (1964) is shown through center of glacier.

DATA SOURCES

Fryxell (1935) provided the first known detailed description of Teton Glacier from his visits to the area during the summers of 1926 through 1931. In 1949 and 1950, Jepson is credited with the first surveys of Teton Glacier which were never published (Reed, 1964). The first published map of Teton Glacier was produced by Reed (1964), from aerial photographs of Teton Glacier taken July 22, 1954. On August 16-17, 1963, Reed performed a plane table survey of the lower portion of the glacier. Reed (1964) produced a map of both surfaces on mylar at a scale of 1" = 500' and included some earlier unpublished information.

In 1994, Elder, Greenwood, and others collected 1040 surface elevations during a topographic survey of the glacier using an electronic total station (ETS) and a Global Positioning System (GPS) unit. A map was produced in metric units with two-meter contour interval and tied the three control points Reed used in his 1963 survey of the glacier. Accuracy of the map is considered high. However, the upper accumulation area particularly around the icefall is poorly represented due to safety concerns and line-of-sight issues.

METHODS

Creating the Surfaces

The 1954 and 1963 surfaces were digitized using Reed's map in AutoCAD due to the limited number of survey control points identified in Reed's Survey. The 1963 survey was performed using three control points based upon an arbitrary datum. To properly reference the map, the Universal Transverse Mercator (UTM) coordinates of the three control points were determined during the 1994 survey. The elevations of the 1954 and 1963 contours were adjusted and converted from English to SI units. The 1994 survey was created using UTM coordinate system and SI units. Once the files were checked for proper position, they were exported in an AutoCAD .dxf release 12 format.

To compare the glacier surfaces for each year, the surveys were converted from AutoCAD drawings to ARC/INFO lattices through a series of steps. The steps include the conversion from AutoCAD .dxf files to ARC/INFO coverages. A coverage is a directory of files containing attribute and spatial information about a vector data set (Zeiler, 1997). Each coverage went through a 2-step conversion to a triangular irregular network (TIN) and then a lattice. A TIN is a representation of a surface by a network of triangles connecting 3-dimensional points. Elevations between points are determined by linear interpolation. A lattice is the representation of a surface by an array of grid cells using elevation information. Elevations between grid points are interpolated by using the neighboring grid cells. In this project, lattices were used because of smaller storage requirements and the ease to view the surfaces in a 3-dimensional perspective.

Comparison of Surfaces

To compare the lattices created from each of the surveys, the enclosed area described by coordinates of each surface must be the same. A new surface representing the elevation differences between the two compared surfaces is created. A view of each surface, the resultant surface from each comparison, and the transect profile of each surface were produced. The following discussion includes changes in surface area, elevation, volume, glacier profiles and change of glacier profiles along the established transect.

Area and Length

Each of the three glacier areas and lengths along the transect (Figure 2) were calculated (Table 1). The percent change in glacier size over the 40 year period is –12.6. It should be noted that the survey from 1994 does not accurately describe the accumulation area due to the dangers from the icefall, crevasses, avalanches and falling rock debris. Retreat of the glacier's terminus during the 1954 to 1994 period was 32 m.

	1954	1963	1994
Area (m^2)	309,000	294,000	270,000
Length (m)	1092	N/A	1060

Table 1 – Area and Length of Teton Glacier

Elevation

Elevation of the glacier is not expected to change markedly since the glacier is contained within a cirque. The elevation at the terminus increased 17 m from 1954 to 1994. The maximum elevation in the accumulation zone decreased 49 m from 1954 to 1994 (Table 2).

	1954	1963	1994
Minimum (m)	3079	3079	3096
Maximum (m)	3520	N/A	3471

Table 2 – Teton Glacier Elevation

Volume

Volume differences between surfaces were calculated using a surface subtraction method procedure in ARC/INFO. The values computed represent the changes in glacier volume that are produced by subtracting the more recent surfaces from the preceding surfaces. The balance is simply the difference between the surfaces.

The result of subtracting an older larger surface from a more recent smaller surface results in a negative balance. This implies that a glacier has lost material, usually accomplished by melting and has either receded or stagnated and down-wasted. The result of subtracting an older smaller surface from a more recent larger surface is a positive balance. A positive balance indicates that an excess of material must be gained to produce the larger surface, usually accomplished by accumulation. This implies that a glacier has grown. The rate of change between surfaces can be estimated by comparing the change in volume to the change in time between observations. The fact that the 1954-1994 balance is negative implies that Teton Glacier is decreasing and the magnitude of the difference implies that it is decreasing by an average loss of 26,000 m^3 yr^{-1}. The average change in height is –4.0 m over the study period. Surface statistics for the compared surfaces are summarized in Table 3. The comparable area reported in Table 3 is smaller than the average glacier area because it represents the total mutual area of the glacier surfaces that was used in the analysis.

	1954- 1963	1963-1994	1954-1994
Comparable Area (m^2)	210,000	204,000	262,000
Ablation (m^3)	308,000	191,000	618,000
Accumulation (m^3)	681,000	1,146,000	1,661,000
Balance (m^3)	-373,000	-955,000	-1,043,000
Average Change (m)	-1.7	-4.7	-4.0

Table 3 - Volumetric Change of Teton Glacier

Profiles

Reed (1964) established a central transect for Teton Glacier (Figure 2). The profiles along this transect were produced for the lower portions of the glacier for 1954, 1963, and 1966 on Reed's map. These profiles clearly show a decrease in surface elevation for the lower portion of the glacier. The same transect has been used to determine the 1954, 1963, and 1994 profiles from the generated surfaces. The difference in length of the profiles represents the change in the glacier surface, or in the case of the 1963 surface, the extent of the survey. Elevations were calculated every 25 m along the length of the transect (Figure 3).

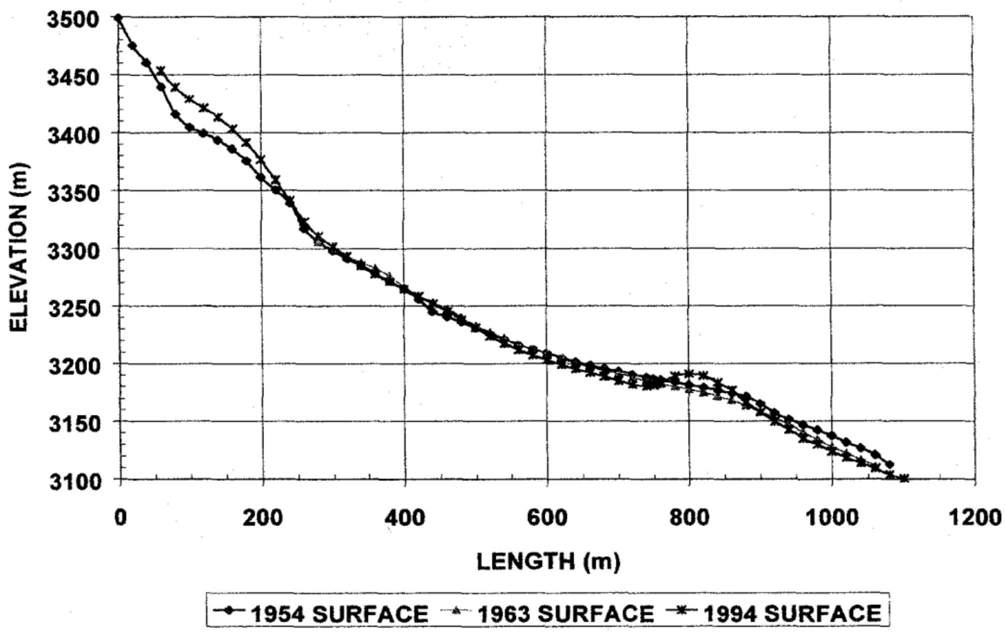

Figure 3 - Surface Profiles of Teton Glacier

The change along the transect represents the difference in elevation between two surfaces. The change in height along the transect is the result of accumulation and ablation periods over the time considered. Positive values indicate that the elevation has increased (gained mass) from the earlier year (smaller surface) to the latter year (larger surface). Negative values indicate that the elevation has decreased (lost mass) from the earlier year (larger surface) to the latter year (smaller surface) (Table 4).

	1954- 1963	1963-1994	1954-1994
Change (m)	-1.8	-1.4	0.7

Table 4 - Average Transect Change

The 1954 – 1963 change in mean profile elevation represents an average loss of mass along the transect of -1.8 meters (Figure 4). The 1963 – 1994 change in mean profile elevation is –1.4 meters (Figure 4) and the overall change in profile is represented by the change in mean profile from 1954 – 1994 (Figure 5). Note that over most of the transect there is a net loss in elevation between the 1954 and the 1994 surfaces. The positive mean value of 0.7 m in Table 4 reflects the large positive difference seen in the accumulation zone (Figure 3).

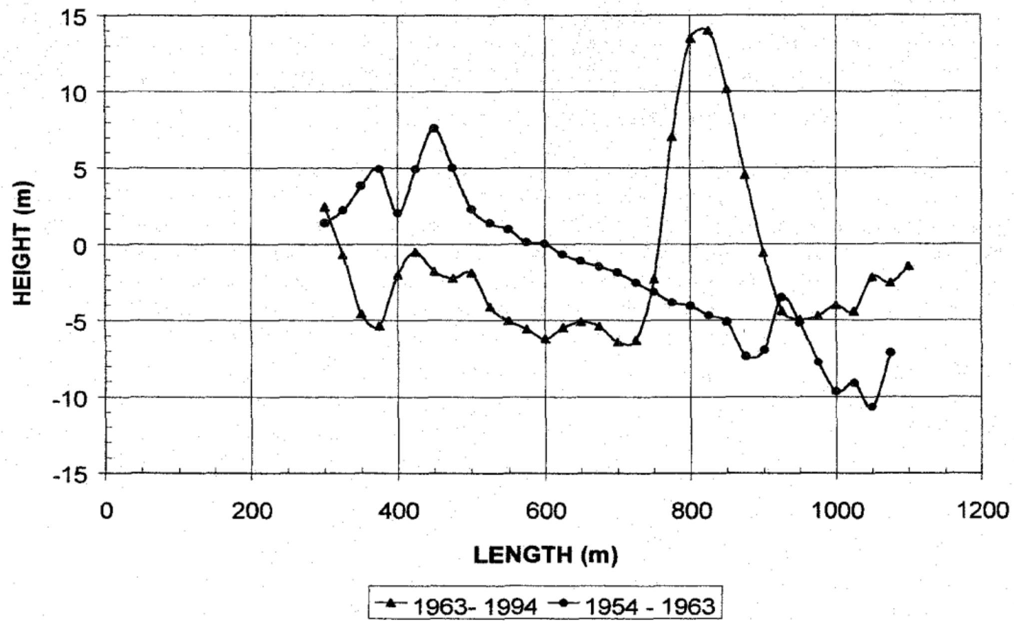

Figure 4 – Changes in Surface Elevation

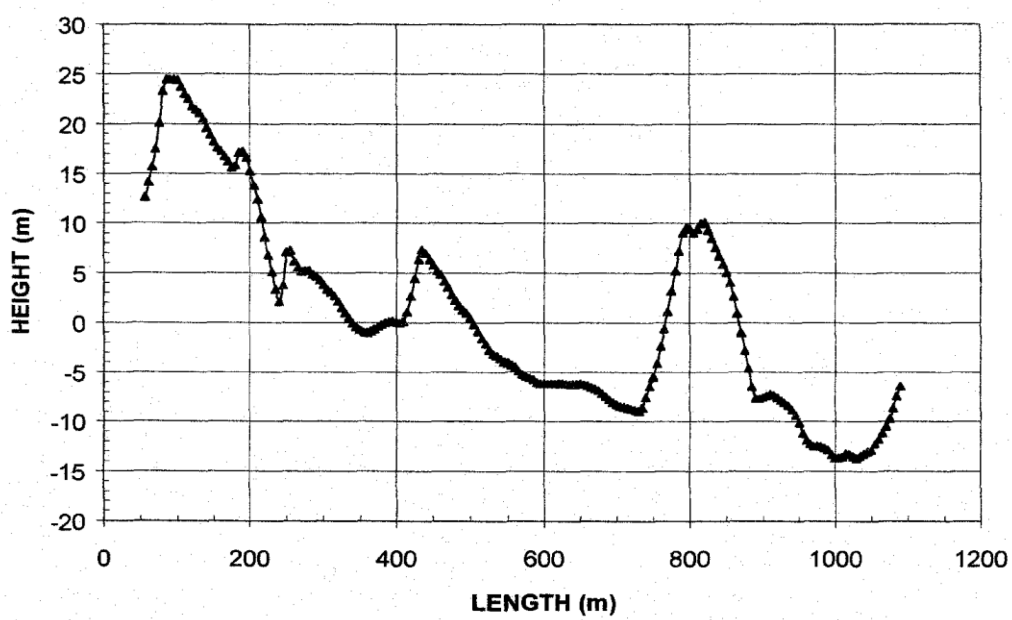

Figure 6 – Change in Surface Elevation: 1954 - 1994

UNCERTAINTY

The results of the comparison of the surfaces is not a mass balance in a traditional sense since the information was not collected at a yearly fixed date or at the end of the ablation season. The glacier surface of 1954 was derived from aerial photographs dated July 22, 1954. The 1963 glacier surface was surveyed August 16-17, 1963. The 1994 glacier surface was surveyed September 9-10, 1994. The comparison does represent the change of the glacier between each period.

Estimation of the errors involved in the project is difficult to calculate. There are a number of uncertainties associated with each step of the project. Errors associated with proper geo-referencing are difficult to quantify due to the number of possible scenarios. A small horizontal shift in the area of the icefall can lead to large volume errors due to the steep terrain. The accuracy of the 1954 surface, created from aerial photographs, is unknown.

The original 1954 and 1963 maps were hand-drawn ink mylars. The 1963 surface was created from Reed's (1964) plane table survey. The 1963 survey did not include the upper portion of the glacier. Calculations of volume change between 1954 and 1963 consider only the portion of the glacier mapped in 1963. Both the 1953 and 1963 maps were established using an arbitrary datum in the English system of units. These maps were digitized using the UTM coordinates identified during the 1994 survey. The contours were corrected for the elevation change and converted to SI units. The 1994 survey has limited accuracy of the upper portion of the glacier because of safety concerns. All maps had to be converted from AutoCAD to ARC/INFO. Errors associated with this process are believed to be minimal because the process was the same for each surface.

Definition of the margin of the glacier extent for each year is an estimate. Steep chutes contributing snow to the glacier obscure the extent and elevation of the glacier margin. Additional difficulties in determining the boundary of the lower portions of the glacier exist due to debris cover.

CONCLUSION

A series of maps were created and converted to ARC/INFO lattices for comparison. The comparison interval ranges from ten to forty years. Only the last survey, 1994, attempts to record the end of the ablation period for the year. Quantification of mass change has been calculated for each interval as well as for the entire length of record. Quantification of errors involved has not been determined and since there are numerous sources of error, the numbers should represent only the general trend in the nature of the glacier's mass.

The glacier's area has decreased and the elevation of the glacier terminus has risen 32 m from 1954 to 1994.

The mass balance for Teton Glacier for the period of 1954 to 1994 is estimated as an average loss of 26,000 m^3 yr^{-1}. The period average implies that the glacier is slowly ablating. It is important that mass balances continue to be calculated for Teton Glacier for a number of reasons. While Teton Glacier does not appear to play an important role in existing water supplies, it does establish a regional indicator of changes in perennial snow and ice masses.

Additional surveys from future years can be added to the record and analyzed. This process offers promise to be able to create additional records and to increase existing records to the limited glacier mass balance database.

ACKNOWLEDGEMENTS

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