

Winter Mass Balance Measurements on Teton Glacier

Begin to Build Basis for Predicting Seasonal Melt and Runoff

Water resources in the western United States are gaining attention as both our perception and reality point toward future shortages. Persons and organizations interested in agricultural, hydropower, municipal, and recreational water use now are showing keen interest in every drop flowing down western rivers. In many cases the rivers are over-allocated and demand exceeds the supply.

The greater Yellowstone region encompasses headwater basins critical to some of the most important water sources in our nation, including the Columbia, Colorado, and Missouri River basins. Grand Teton National Park (NP) contains one reservoir dedicated to agricultural water storage and the supply to this reservoir is primarily from snowmelt. The reservoir, which predates the park's establishment, is the first in a long list of containments on the Snake River.

In order to manage water resources efficiently and realistically, we need to improve our methods of prediction for supply and runoff. Uncertainty about climate change makes our predictive capabilities subject to considerable error. In mid-latitude alpine regions much of the annual precipitation is stored as snow during the winter. Slight changes in climate may make large differences in the amount of precipitation and storage in the form of snow. Glaciers offer a long-term record of climate by storing information lost in the seasonal snowpack which melts annually on nonglacier surfaces.

Mass balance, the gains and losses of ice mass over time from a glacier, is the primary parameter with which we can couple glaciers to climate changes (Meir, 1992). There is evidence that the Earth's ice sheets are not decreasing in volume (Bentley and Giovinetto, 1992), and that the observed rise in global sea level may be attributed partly to negative mass balance in mountain glacial systems (Meier, 1984; Jacobs and Hellmer, 1992). Small alpine glaciers such as Teton Glacier in Grand Teton NP are more sensitive to climate change than larger glaciers and ice sheets, providing relatively accessible information about subtle changes in modern climate. However, detailed mass balance measurements rarely are made and measurement data spanning more than a decade are scarcer still.

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Figure 1. Teton Glacier surrounded by the Grand Teton on the left, Mount Owen in the center, and Mount Teewinot to the right. Teton Glacier occupies the shaded cirque in the center of the photograph below Gunsight Notch. The glacier's large terminal moraine extends from the East Ridge of the Grand Teton. This photo was taken from the east after the first significant snowfall in October 1993.

The National Park Service has acknowledged the importance of glacier studies in Global Change research and, in particular, detection of climate change through mass balance changes (National Park Service, no date). Glaciers of Grand Teton NP offer unique opportunities for climate change studies relating to the entire Greater Yellowstone Ecosystem.

When winter snow accumulation is measured at, or close to, the date of its peak, an estimate of winter mass balance can be made. A similar survey at the date of minimum snow cover, at the end of the ablation season, gives a value of summer mass balance. A multi-year record of summer and winter mass balance provides clues to changes in overall glacier mass balance resulting from climate perturbations. Seasonal snowpack mass is measured in terms of snow water equivalence (SWE). SWE is simply the amount of water that would be produced if the snow were melted simultaneously at a point, or if the depth of snow were multiplied by the snow density where density is expressed as the percent of the density of water.

Results reported are the first of a series of surveys designed to measure winter and summer mass balance of Teton Glacier. These measurements will be a valuable baseline for future climate change studies carried out in the region. This research project also demonstrates the value in using GIS techniques to extrapolate from point measurements to spatial estimates of snow water equivalence.

Study Site

Teton Glacier is located in the Teton Range of Wyoming. The glacier lies within Grand Teton NP at about 43°44'30"N and 110°47'31"W (4,842,985 N and 516,755 E UTM) and ranges between 3,095m and 3,500m above sea level. Teton Glacier occupies a deep cirque surrounded by steep walls of the Grand Teton (4,196m) to the south and Mount Owen (3,937m) to the north (Fig. 1).

Methods

To calculate SWE, systematic field measurements of snow depth and density were gathered from May 17 through 20, 1993, the time of peak snow accumulation for the year.

To measure density, snow pits were dug at two sites, with dual snow density profiles. Snow temperature and stratigraphy also were observed and recorded. From these values an estimate of density as a function of snow depth was derived.

Aluminum probes were used to measure snow depths at intervals of approximately 10 meters along 5 major transects (Figs. 2 through 4). One vertical transect extended the length of the glacier from the terminal moraine to the head of the accumulation area, while four horizontal transects were positioned across the first. Five additional point measurements were made at locations where probing was too difficult for an entire transect to be completed. In all, 201 depth measurements were made. From these depth values, combined with density values from the snow pits, SWE (depth x density) at points along the transects were calculated.

Further analysis required addressing a classic geographic question: How do we distribute point values over a surface? Many attempts have been made to do this in glacio-

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logical contexts (e.g. Young, 1974 and 1975; Paterson, 1981; Elder et al., 1992; Elder and Yang, 1992). Four interpolation techniques for modeling such a distribution of SWE over the glacial surface were selected for comparison. Each required elevation as an input for calculation. While elevation does not itself affect snow distribution, it works well in many cases as an index for physical processes that do (i.e. temperature, precipitation).

Estimates of elevation for each probe site might be obtained by relating field collection locations to an established topographic surface, such as a USGS 1:24,000 contour map. However, geographic information systems (GIS) can create and use computerized equivalents of such maps. Comprised of cell grids covering the area of interest, these digital elevation models (DEM) have elevation values assigned to each cell throughout the coverage. Thus, any mapped site is automatically assigned the elevation for the cell upon which it falls.

Constructing a Digital Elevation Model

The standard USGS 30m DEM did not offer sufficient resolution or accuracy to be used in the data analysis. As an alternative, maps were located from USGS field studies (Reed, 1964), which presented 1954 and 1963 margins and contour lines for the glacier. When processed into a digital elevation model, these maps provided the necessary DEM. From the digitized version of this map, a DEM was generated at 5m resolution using GRASS (GIS) software. The choice of cell size ensured that field data, collected at 10 m intervals, would occupy separate cells when referenced back to the map.

Registering field locations to such a DEM was the next step to make the map functional. Probe sites originally were marked off in sequence along each transect from an established point in the field. Distances between successive sites were measured while traveling up the glacier surface from each previous point. Sequential points measured along an ascending slope will, necessarily, lie closer together when placed upon a flat map. Slope and azimuth determined at each field location were used to calculate the corresponding horizontal distance traveled. The resultant UTM coordinate pair represented the proper location on the Reed map for each field site. All field points now took their correct locations within the digitized map margins and the elevations value for each on the DEM could be applied to its respective field position. The 5m DEM and locations of the field measurements are shown in Figure 5.

SWE at all points now could be estimated as a function of elevation. Models programmed across the entire surface resulted in estimates of SWE volume for the entire snowpack. In addition, the average SWE



Figure 2. Field hand Martin Hagen with portable depth probe in the ice fall portion of the glacier. Note the crevasses in the background common in this section. The photograph was taken during field work in September 1993.

was calculated as the total volume divided by the area of the glacier. A second feature of DEMs is the capability of deriving distributed slope and aspect cell values from their corresponding elevations. Using these values to locate areas of steep slope, an index of avalanche probability was defined upon the surface. These areas accounted for additional snow depth due to local redistribution of snow by avalanching.

Modeling Snow Water Equivalence

Four methods of interpolating the depth and density measurements were used. These included: (1) dividing the glacier into evenly spaced elevation zones and assigning the mean of all the measurements within each zone to that zone; (2) linear regression of measurements against elevation; (3) binary regression tree using elevation as the independent variable, and (4) binary regression tree using elevation and an index of avalanche activity as independent variables.

The first two methods are conventional techniques often applied in glaciological and hydrological studies; the binary tree classifier was experimental in the glaciological context and was used here in an attempt to better refine the model and to introduce one element of snow redistribution.

Results

The binary regression tree method using elevation and the avalanche index as independent variables provided the most accurate distribution of snow based on statistical analy-

ses of the field data. Figure 6 shows the results of the binary regression tree method using elevation and the avalanche index. Based on the models, the best estimate of mean snow depth on the glacier was about 6.85m. The best estimate of mean snow water equivalence was 3.22m with a total volume of about 970,000m³. The other modeling methods produced similar estimates of total snow storage on the glacier, but they differed significantly in the distribution of the snow over the glacier surface.

The 1993 water year was just below normal for snow accumulation based on long-term measurement stations in the region (Wyoming Basin Outlook Reports, 1993). "Normal" in this context is defined as the 30-year mean, taken from 1961 to 1990. Martner (1986, p. 79) shows an isohyetal map of annual precipitation that places the Teton Range within the 1.5m (60") isohyet. This estimate is based on a complex relationship between topographical information and long-term precipitation and snowpack measurements, both of which are sparse in mountain areas. Martner (1986, p. 84) shows the Teton Range receiving less than 20 percent of annual accumulation during the months of June through August. Subtracting out 20 percent for summer precipitation, the winter accumulation based on the isohyetal map would be about 1.20m water equivalent. Although the values in Martner's map must be applied with caution, we can compare



Figure 3. Rod Newcomb and Robbie Fuller take a depth measurement in an avalanche debris cone on the southeast margin of the glacier. Gunsight Notch is in the background between the flanks of the Grand Teton on the left and Mount Owen on the right.



Figure 4. Martin Hagen in the accumulation zone above the ice fall. Snow depths in the area averaged greater than 10m. Mount Teewinot is in the background.

them to our modeled results for accumulation on Teton Glacier. The expected aerial average from Martner of 1.20m compared to our modeled accumulation of 3.22m shows 2.7 times the expected value.

It is believed that the high value of accumulation is attributable to high rates of orographic precipitation, leeward deposition of suspended snow load, and redistribution of local accumulation by avalanching on to the glacier from surrounding slopes. Teton Glacier occupies a deep cirque flanked by the two highest peaks in the range. These peaks, and the arete between them, lie to the west or windward side of the glacier, effectively creating the largest eddy or potential lee-side deposition area in the range. This fact, combined with avalanching and the southerly blockage of solar irradiance, gives the cirque a high accumulation potential. Note that most of the other east-facing cirques in the Tetons do not contain glaciers.

The accumulation gradient observed on the glacier is remarkable. The gradient was calculated for the cirque area covered by field measurements using linear regression of SWE based on elevation. Using only the field data, a value of 0.84m SWE per 100 m elevation gain was found. The large gradient is applicable to this portion of the cirque only; it predicts no snow cover below an elevation of about 2,900 m elevation which is contradictory to the existence of substantial snow cover in the valley floor at 2,080m. Other localized cirques in the range with similar morphometry may have such accumulation gradients.

Summary

This study has produced two relevant conclusions. The first is that seasonal snow inputs to Teton Glacier may be a great deal larger than expected for the region. The second is that although a neophyte statistical modeling technique, the binary regression methods may prove to be a useful tool in mass balance estimation on glaciers with variable accumulation patterns (Chambers, 1992), complex topography (Kuhn et al., 1985) and where a glacier exists over a variety of climate conditions (e.g. accumulation area in the alpine with the toe at sea level).

The conclusions and analytical methods applied in this study are valid for the 1993 water year only. Accumulation in the region was close to normal, and it is believed that the distribution of snow on the glacier was typical of normal years. More years of field work

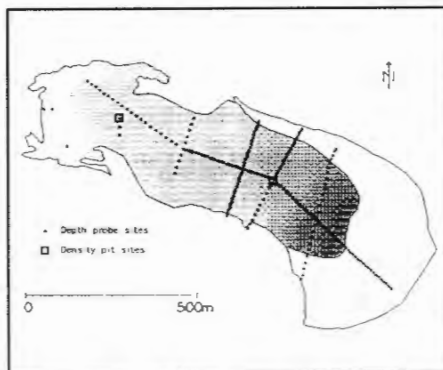


Figure 5. Digital map of 5m DEM constructed from contour map (see Fig. 3). Lighter shades represent higher elevations; darker shades, lower elevations. The line dissecting the area from top to bottom is the approximate terminus of the glacier. The line to the east of the present glacier area represents the terminal extent and moraine of the glacier at its maximum during the "Little Ice Age."

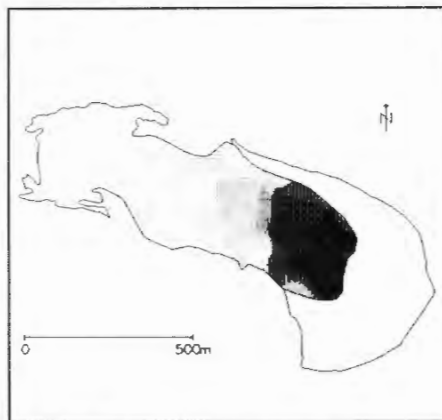


Figure 6. Digital map of snow water equivalence on the glacier surface. Snow was mapped using a binary regression tree with elevation and an avalanche index as independent variables. Lighter shades represent areas of greater snow accumulations; darker shades, shallower snowpack areas.

and analysis are needed on Teton Glacier before any of the results can be taken as normal. Additional years of field data collection and analysis will allow us to establish "average" accumulation and melt patterns, so that we can then attempt to predict changes in seasonal melt and runoff that may accompany changes in regional precipitation and temperature.

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