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The performance of a simple degree-day estimate of snow accumulation to an alpine watershed

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ABSTRACT We estimated the yearly snow accumulation to the Glacier Lakes Ecosystems Experiments Site (GLEES) for the winters of 1987-88, 1988-89, and 1989-90, using a simple degree-day model developed by J. Martinec and A. Rango. Comparisons with other data indicate that the estimates are accurate. In particular, a calibration with an intensive snow core-probe survey in 1989-90 agrees within the probable error of the survey, which was $\pm$ 6%.

SITE DESCRIPTION

The Glacier Lakes Ecosystems Experiments Site (GLEES) is located in southeastern Wyoming (Musselman, in prep.). It contains three adjacent small watersheds, each draining to a small lake; East Glacier Lake (EGL), West Glacier Lake (WGL), and Lost Lake (figure 1). The three lakes are at an altitude of about 3300 m, situated beneath a northeast- southwest ridge which is about 3450 m in altitude. The watershed areas measured: GLEES, 287 ha; EGL, 28.6 ha; and WGL, 60.6 ha. The WGL watershed includes a permanent snowfield which has a significant effect on the

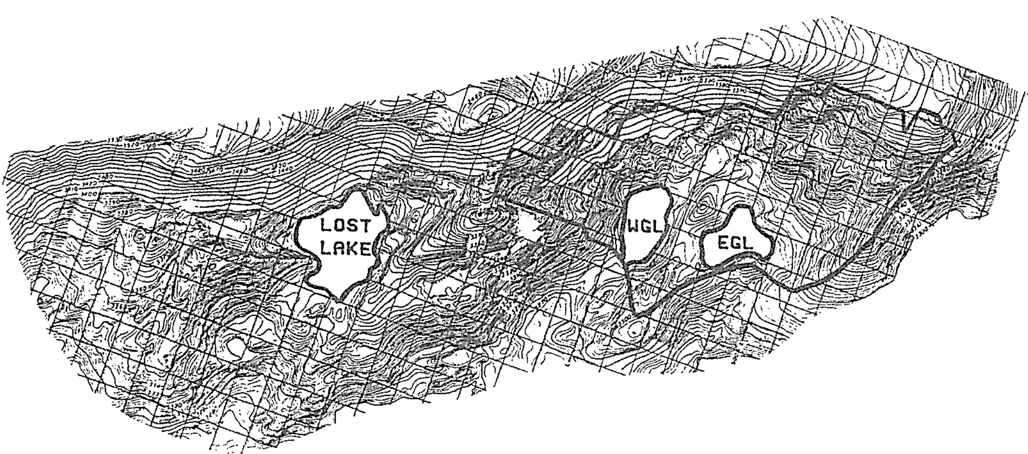

FIG. 1 The Glacier Lakes Ecosystems Experiments Site. The solid line indicates the snow survey area. The grid spacing is 100 m.

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water balance while the EGL looses all of its snow each season. The Lost Lake watershed is not considered separately from the GLEES in this paper. The outputs of East and West Glacier Lakes are monitored by means of Parshall flumes. Intensive ecological studies are being conducted at the GLEES with the goal of a better understanding of alpine- subalpine ecosystems.

Snow is an important part of such ecosystems in many climates and is particularly important in the GLEES. Snow accumulates for 6 months of the year and seasonal snow is present for 8 months. Therefore, an accurate estimate of the yearly snow accumulation into the site is critical to many of the other studies being conducted. For example, input-output chemical balances are being determined as a part of studies of the chemical climate. Chemical concentrations in various hydrological components of the watersheds are monitored. Converting the concentrations to loads, consumption, and production requires accurate estimates of the water quantity flowing through the hydrological components.

METHODS FOR SNOW ACCUMULATION ESTIMATES

Snow accumulation is difficult to estimate, especially in windy environments such as the GLEES where the yearly mean wind speed is 34 km/h. We are investigating a combination of methods in an attempt to identify one, that is practical for long-term monitoring and whose accuracy is verifiable.

Snow core-probe surveys

Direct snow core measurement of water equivalent taken over the area is probably the most reliable of the snow accumulation estimators. One disadvantage of this method is that very intensive sampling is necessary, especially in this windy environment where the wind redistributes the snow into a snowpack with highly variable depth. From the results of Elder et al. (1989) we estimate that 1500 to 2000 sample points would be necessary to achieve $\pm$ 5% accuracy in sampling an alpine-subalpine area with the size of GLEES. In general, the variability in depth is much greater than the variability in density, especially at the start of melt. This fact led Bartos (1970) to conclude that snow depth probes can be used as a substitute for four out of five snow cores, with a considerable saving in effort. Even with this saving, the effort involved in producing a core-probe survey is large.

In addition, the wind causes extensive cornicing on the top of the steep ridge to the north. Results presented below show that these regions contribute significantly to the water balance in the area. However, it is dangerous to use snow core techniques to measure the amount of snow in this cornice and below it because of the high probability of avalanches.

Precipitation gages

As part of the permanent instrumentation a precipitation gage had been placed between East and West Glacier Lakes and on the west side of WGL near its outlet. It is well documented that precipitation gages underestimate the amount of snow accumulation in windy environments. In addition to their usual problems, the operation of precipitation gages in the GLEES is extremely sensitive to gage location because of the complicated terrain and air flow patterns. Wind patterns in the GLEES are mainly determined by the terrain and are not representative for the regional wind (Wooldridge et al., in prep.). The snow trapped in the cornice along the ridge top is prevented from reaching the gages but contributes to the water flow through the GLEES (Hasfurther et al., 1990). These considerations show that the precipitation gage measurements cannot be used as a standard to calibrate other methods of estimating snow accumulation in the GLEES.

Martinec-Rango model

A snowmelt runoff model has been proposed by Martinec and Rango (1986). The snowmelt part of the model is based on a simple degree-day correlation with the depth of snowmelt (Martinec and Rango, 1981),

$$H_d = 1.1\, D_s\, T_d\, A_d$$

where H_d is the daily water equivalent of the snowmelt, D_s is the snow density, T_d is the degree-days above 0°C for the day, and A_d is the areal coverage of snow for that day. The daily melt for the season can be summed to provide an estimate of the yearly accumulation.

This model is attractive for estimating yearly snow accumulation because of its limited data requirements. D_s can be determined with a relatively small number of samples at the initiation of snowmelt (Bartos, 1972). It tends to a constant from year to year, and is relatively easily estimated as snowmelt progresses (Martinec and Rango 1986). The areal coverage A_d can be estimated from a small number of aerial photos (Rango, 1990) because the relationship between areal coverage and degree-days gives a smooth curve that can be determined to acceptable accuracy with a few points. The sparse nature of the tree coverage in the alpine-subalpine aids in an accurate estimate of areal snow coverage from aerial photos. The temperature at the GLEES is recorded every 15 minutes from a meteorological station, providing data for determining the degree-days above 0°C.

The major drawback of the Martinec-Rango (M-R) model is that it is not based on verifiable physical processes. Therefore, its accuracy and year-to-year consistency must be tested in the GLEES before it can be relied on for routine monitoring.

Snow recession curves are shown in figure 2 for the GLEES, the EGL, and the WGL watersheds. The influence of the permanent snowfields is apparent in the GLEES and the WGL plots. The curves change slope at about degree-day 700 for 1987-88, 400 for 1988-89, and 500 for 1989-90; thereafter they show only a small decrease in snow covered area. The EGL plot decreases to zero snow cover at about the same time the other curves change slope because there is no permanent snowfield in this watershed. For the estimates that follow, the M-R model was run until degree-day 700. This accounts for the seasonal snow cover but not the continuing output of the permanent snowfield or the addition caused by rain. Where those additions affect the conclusions, they are added to the estimate.

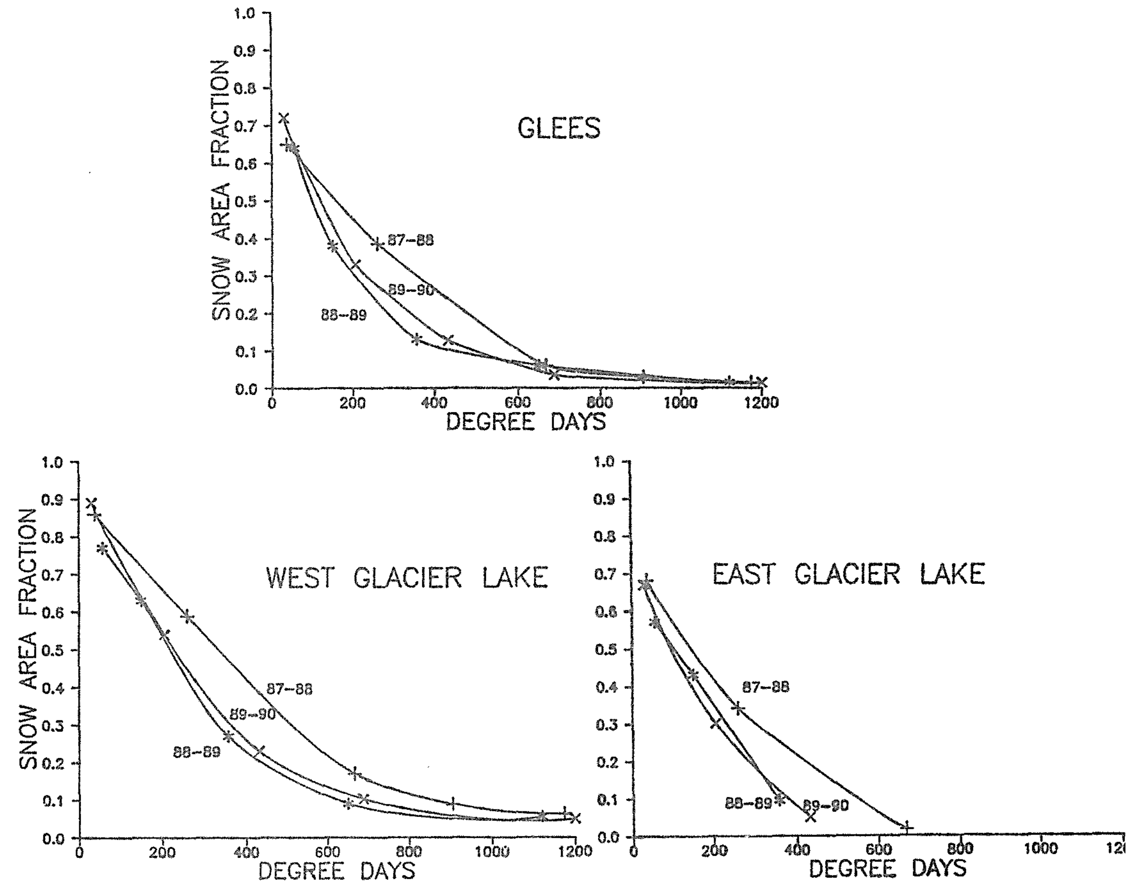

FIG. 2 Snow area fraction vs Degree-day for the three areas studied.

Watershed runoff measurements

The amount of water leaving a watershed must equal the input amount, minus the losses. Uncertainties in subsurface hydrology, evaporation, evapotranspiration, and outflow gaging can add significant errors to the input- output calculations. However, it is usually possible to put bounds on those errors. The input-output calculations will usually indicate whether or not there are gross errors in the measurements and estimates. An additional complication for this paper is the fact that the WGL gage had an observed leak in 1988, which was repaired in late 1988 (Hasfurther et al., 1990). The effect of the leak on the runoff measurements is discussed below.

Tree morphology estimates of snow depth

The snowpack affects alpine-subalpine trees in two ways. It protects those parts of the trees below the snow surface from wind drying and abrasion from blowing snow. In the spring, those parts below the snow surface are subject to fungus diseases. These effects are apparent in the tree morphology in the alpine-subalpine and can be used to estimate a long-term average snow depth (Wooldridge et al., 1990; Sommerfeld et al., 1990). However, this method is subject to a systematic error that tends toward a low estimate, but whose magnitude is difficult to estimate. Thus, the results form a lower bound to possible estimates but must themselves be calibrated to provide accurate long- term estimates of snow accumulation.

Soil Conservation Service snow course

The USDA Soil Conservation Service has maintained a snow course at Brooklyn Lake, about 1 km from the GLEES. The snow course data do not provide accurate estimates of the yearly snow accumulation but they do provide a year-to-year comparison that can be used as a test of the year-to-year consistency of other methods of estimating the accumulation.

SNOW ACCUMULATION ESTIMATES IN THE GLEES

We have made estimates of the snow accumulation in the GLEES for the winters 1987-88, 1988-89, and 1989-90. The estimates for 1987-88 have been evaluated by intercomparison among the different methods and estimates of possible errors (Sommerfeld et al. 1990). The conclusion from the intercomparisons was that the accuracy of the M-R estimate of snow accumulation was between ± 10% and ± 20%. The data are now available for intercomparison of the estimates for 1987-88, 1988-89, and 1989-90. Parshall flume data are available for 1988 and 1989, which allows comparison of the snow accumulation with the outflow of East and West Glacier Lakes. For the winter of 1989-90, we conducted an intensive snow core-probe survey at peak snow accumulation. This survey provides an accurate basis for calibration of the M-R model.

1987-88

The winter 1987-88 was the first winter we estimated the snow accumulation in the GLEES using the Martinec-Rango (1986) degree-day model. We evaluated the results of that method using estimates from precipitation gages and tree morphology, then corrected the tree morphology for the particular year using data from a Soil Conservation Service (SCS) snow course near the southern edge of the GLEES. The SCS data indicated that the 1987-88 snow accumulation was 91% of the 25-year average.

The methods, assumptions and results are described in Sommerfeld et al. (1990); the M-R results given here are somewhat different. Here we use more complete density estimates derived from the 1990 snow core survey described below. We also use the first degree-day above 0° C as the model starting date because that starting date gave the best agreement between the 1989-90 M-R calculations and the 1989-90 snow survey described below. A different starting date was used in Sommerfeld et al. (1990).

Martinec-Rango estimate The estimated snow input to EGL was 99.0 cm H_2O and to WGL, 208.1 cm. The total for the GLEES was 109.9 cm H_2O.

Precipitation gages Two precipitation gages were in operation at the GLEES during winter 1987-88. One located between East and West Glacier Lakes is shielded with a Wyoming Shield. It accumulated 68 cm H_2O, considerably less than estimated by the M-R method. The precipitation gage at the National Acid Deposition Program (NADP) site west of WGL accumulated 92 cm H_2O. The site between the lakes is on the top of a small, windy ridge that is usually blown clear of snow. The NADP site is in an accumulation zone.

Tree morphology From the tree morphology on the GLEES, Wooldridge et al. (1989) and Sommerfeld et al. (1990) estimate an average snow height of 200 cm. The estimate is thought to contain a systematic error biasing it toward a low estimate. If we use the M-R estimate of 110 cm H_2O and an average density of 0.454 Mg m^3 as measured by the 1990 snow survey described below, the average snow height would be 241 cm, 20% higher than the tree morphology estimate.

Watershed runoff The EGL output corresponded to 73.7 cm H_2O on the watershed, based on a watershed area of 28.65 ha. The WGL output corresponded to 132.3 cm H_2O on an area of 60.65 ha. The estimated snow input plus rain (11.5 cm H_2O) and permanent snowfield (20 cm H_2O) were: EGL, 99.0 + 11.5 = 110.5 cm H_2O; WGL, 208.1 + 11.5 + 20 = 239.6 cm H_2O.

The WGL/EGL ratio of the estimated water equivalent inputs is 2.17. The WGL/EGL ratio of the flume measurements is 1.79. The WGL flume had an observed leak in 1988 resulting in a low systematic error which may account for the difference.

1988-89

Martinec-Rango estimate The M-R estimate for 1988-89 for GLEES was 96.6 cm H_2O; for EGL, 67.8 cm, and for WGL 154.3 cm.

Soil Conservation Service snow course For 1988-89, the SCS Brooklyn Lake snow course results indicated that the snow accumulation was 68% of the 1987-88 accumulation. Assuming that 1987-88 was 91% of average, as indicated by the SCS 1987-88 results, the M-R ratios for the GLEES is 78%, for EGL, 62%, and for WGL, 59%.

Watershed runoff For 1988-89, the water equivalent, including rain and the permanent snowfield effect, for EGL is 67.8 + 19.1 = 86.9 cm H_2O. For WGL it is 154.3 + 19.1 + 20 = 193.4 cm H_2O. The outputs are 57.6 for EGL and 142.6 for WGL. The WGL/EGL ratio of inputs is 2.23 and outputs, 2.48.

1989-90

Martinec-Rango estimate The M-R estimate for 1989-90 is: GLEES, 91.1; EGL, 70.3; and WGL, 140.5 cm H_2O. In addition the core-probe survey area described below has an M-R estimate of 96.0 cm H_2O. The WGL/EGL ratio of the snow input is 2.0.

Snow core-probe survey An area of 144 ha within the GLEES was surveyed on a grid of 25 m (figure 1). In all, 821 points were sampled, 37 with a federal snow corer that measured the depth and water equivalent, and 784 with a snow probe for depth. The survey area is about one-half the area of the GLEES and the number of sample points is within the range estimated from Elders et al. (1989) for ± 5% accuracy. The ratio of core samples to probe samples is about 20:1, considerably higher than the 5:1 recommended by Bartos (1972). However, it is the most complete density data available for this area at the present time. Furthermore, the 95% confidence interval of the mean water equivalents using this limited density data is ± 6%. The result of this survey was 101 cm H_2O averaged over the survey area. The average density calculated from the core samples was 0.454 Mg/m3.

Soil Conservation Service snow course The SCS snow course at Brooklyn Lake gave 70% of the 25-year average for 1989-90. This compares with the M-R estimate for GLEES of 75% assuming that 1987-88 was 91% of normal. For WGL the M- R estimate is 62% of average and for EGL it is 65% of average.

DISCUSSION

The most accurate determination of snow accumulation into the GLEES is derived from the 1989-90 snow core-probe survey. The agreement between the survey's 101 cm H_2O and the M-R estimate of 97 cm H_2O is within the 95% confidence interval of the snow water equivalent determined from the variabilities of the depth and the density measurements.

The comparisons between M-R estimates for the different years is similar to those from the SCS snow course at Brooklyn Lake. The reason for the GLEES estimate being higher while the EGL and WGL estimates are lower than the SCS data for 1988-89 and 1989-90 is not clear. Winter 1987- 88 was close to normal while 1988-89 and 1989-90 were significantly below normal. We speculate that a difference in storm tracks may have produced a different snow distribution in 1987-88 compared to the other 2 years. Large, infrequent storms that usually account for a major portion of the snow, generally have a southwest track, moving snow into the GLEES along the axis of the valley. This should result in a relatively uniform snow accumulation in the GLEES below the ridge. Smaller storms that deposit a larger fraction of the snow during low snow years generally have a northwest track. The snow from these storms are more likely to be trapped in the ridge cornice above West Glacier Lake, resulting in a comparative deficit in the eastern part of the GLEES.

The comparisons between the estimated input to the lake watersheds and their measured outputs give reasonable results. The differences between the two are:

EGL 1987-88 36.8 cm H_2O;
EGL 1988-89 29.3 cm H_2O;
WGL 1987-88 107.3 cm H_2O;
WGL 1988-89 50.8 cm H_2O.

The WGL dam was observed to be leaky in 1987-88 and the leak was repaired for 1988-89, probably explaining the anomalous difference.

The WGL/EGL ratio of inputs is 2.28 and the ratio of outputs is 2.48 for 1988-89. The differences may have two different explanations. We estimated an area of 28.65 ha for the EGL while Hasfurther et al. (1990) estimated 24.7 ha; using Hasfurther et al.'s area would bring the values closer. On the other hand, some flow from EGL to WGL (Hasfurther et al., 1990) would also account for the difference. EGL is 5 m higher than WGL. They are less than 120 m apart and separated by glacial till.

The results from the various comparisons reinforce the conclusions of Sommerfeld et al. (1990) that the Martinec- Rango method can be calibrated for use in monitoring snow accumulation in the GLEES. The results presented here are on the edge of the more pessimistic error evaluation given in Sommerfeld et al. (1990). The difference is due to a different estimate of average snow density at maximum accumulation. The value used here is based on many more samples taken on a grid scheme that is less likely to have systematic errors. The calibration against the snow core- probe survey gives excellent agreement. The comparison between the estimated input and lake output also appears to be well within the range of reasonable values.

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