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Mass balance and runoff of the partially debris-covered Langtang Glacier, Nepal

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Abstract The mass balance and runoff of the Langtang Glacier is calculated using the PTAA (precipitation-temperature-area-altitude) model. Input are meteorological observations at Kathmandu and the area-altitude distribution of the glacier. The glacier area is 75 km2 and its altitude range is from 4500 to 7000 m. The PTAA model converts daily precipitation and temperature observations at the Kathmandu airport to snow accumulation and snow and ice ablation at each of the twenty-five 100 m altitude intervals on the glacier. The simulated annual mass balance for the period of record is -0.11 m(we) and the ELA is 5280 m. Mean summer runoff (June -September), the sum of total simulated ablation and precipitation as rain, is 14 mm per day, which is a rate similar to runoff measured for the nearby Lirung Glacier basin. Simulated ablation also agrees with ablation measurements made on the Lirung Glacier over the same time period and at approximately the same altitude.

INTRODUCTION

The mass balance of glaciers in the Himalaya is an important indicator for global climate-change. These high-altitude, low-latitude glaciers are thought to be more sensitive to small temperature changes than glaciers located at lower altitudes and higher latitudes. In addition, runoff generated by the ablation of these glaciers is a major source of water for the people living in the region, therefore changes in the size of these glaciers is critical for assessing long-term water supplies (Rana et al, 1997).

The Langtang Glacier, located at approximately 28 30 N latitude and 85 30 E Longitude, ranges in altitude from 4500 to 7000 m and has a surface area of 75 km^2. As are many Himalayan glaciers, approximately 47% of the Langtang Glacier is covered by debris, however the debris thickness is unknown (the average thickness on the nearby Lirung Glacier at 4400 m altitude is 0.5 m (Fujita, 1996). The debris cover has a significant effect on ablation rates, and consequently on the glacier's mass balance (Ostrem, 1959; Mattson and Gardener, 1989). This report describes the application of a mass balance model to the Langtang Glacier and compares ablation measured on nearby Lirung Glacier with simulated ablation on the Langtang Glacier during the same time period.

Fig.1 is an oblique photo that shows the upper part of Langtang Glacier.

Fig. 1 Langtang Glacier, Nepal. Photo courtesy of Das Color Lab, Kathmundu, Nepal.

To produce realistic mass balance results, the model takes into account a glacier's unique area-altitude distribution, which has embedded in its surface configuration a link to the past climate. A glacier's surface can be defined by a multitude of individual facets, each one with a different orientation in space (for example, the Langtang Glacier has 3 million if each is defined as having a surface area of 25 m^2). The area-altitude distribution is a rough approximation of these facets, which, in response to current meteorological conditions, determine the glacier's mass balance. The altitude and inclination of each facet are determined by erosion of the underlying bedrock throughout geologic time and thus has recorded the link between mass balance and the climate that prevailed during this period. The energy (by solar radiation and by the turbulent transfer of heat from the surrounding air) and mass (mostly as snow) received by each individual facet determines the glacier's total mass balance. The mass balance controls the discharge of ice, which is the driving force producing glacial erosion. Therefore, a continuous, unbroken time-link between the climate, glacier erosion and mass balance exists today as it has for the past million or more years. The model is calibrated by minimizing the error of regressing several sets of daily balance variables with each other (for example, the balance versus the zero-balance-altitude, or the balance exchange versus the accumulation area ratio), which assumes there is an internal consistency in the link between mass balance and climate that is controlled by the glacier's area-altitude distribution.

THE PTAA MODEL

Two data sets are needed for application of this model to a specific glacier:

1. Meteorological observations from a nearby weather station or stations (daily precipitation and maximum and minimum temperatures).

2. The area-altitude distribution of the glacier (the AA profile).

Input to the model for the Langtang Glacier are daily precipitation and temperature observations at the Kathmandu airport, located 60 km south of the Langtang Glacier and at an altitude of 1546 m. The available temperature record at this site is for 1969 through 1997, and the precipitation record for 1987-1997. Missing temperature observations were reconstructed by interpolating from observations on adjacent days. The precipitation record is complete. Average daily precipitation for the 1987-97 period at Kathmandu is shown in Fig. 2. Both precipitation and temperature observations at Kathmandu closely agree with previously published mean monthly records at this weather station (Wernstadt, 1972).

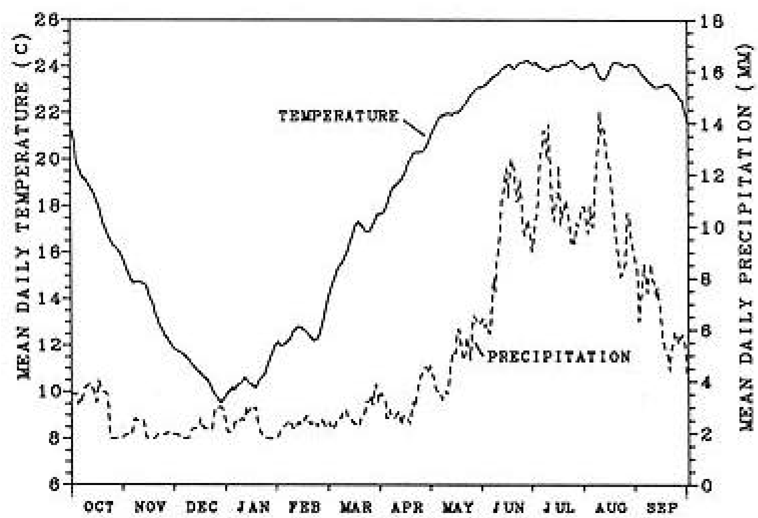

Fig. 2 Mean daily precipitation and temperature at Kathmandu averaged for the 1987-97 period.

The glacier and the surrounding area was digitized by the Department of Meteorology and Hydrology in Kathmandu using a 200 m grid, from a 1:50,000 topographic map (Austrian Alpine Club, 1990). Each grid point was given one of three designations: glacier ice, debris-covered ice, or rock. There were 984 grid-points of glacier ice and 887 grid-points of debris cover, indicating that the total glacier is 74.8 km^2, with 35.5 km^2 of debris cover (47.4 %). Fig. 3 shows the distribution of glacier ice and debris cover. Using the digitized data, the glacier area was divided into twenty-five 100 m altitude intervals. Fig. 4 shows the area-altitude distribution for the total and the debris-cover glacier area.

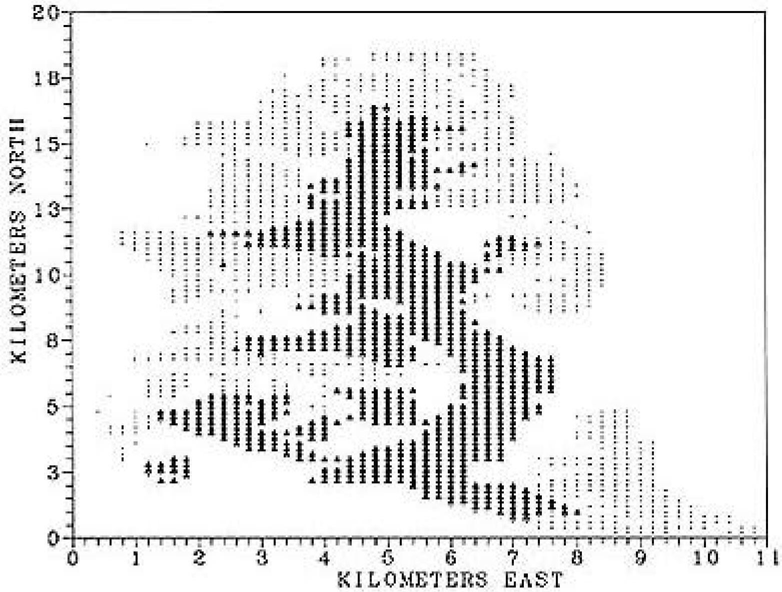

Fig. 3 Results for digitizing the Langtang Glacier on a 200 m grid. The small points designate glacier ice, the large triangles designate debris-cover, which is 47% of the total glacier area of 75 km^2. These data were used to calculate the area-altitude distribution shown in Fig. 4.

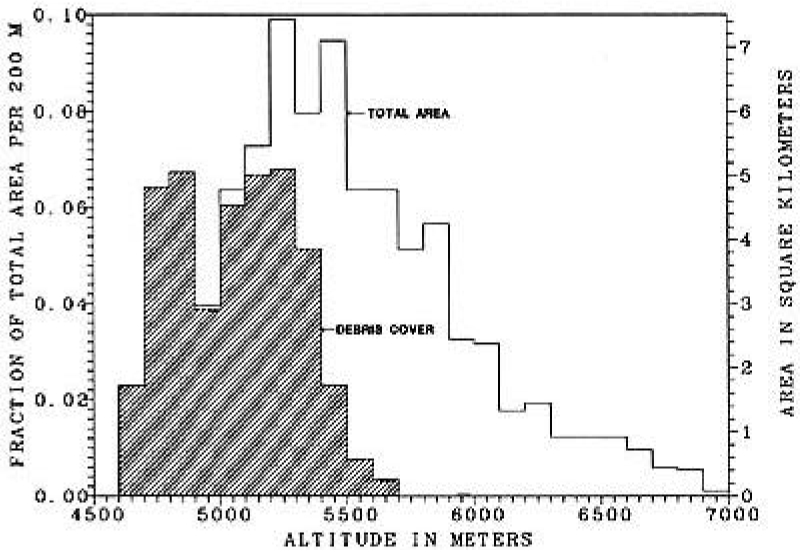

Fig. 4 The area-altitude distribution of the glacier in 100 m increments. The area of each area interval of the glacier that is covered by debris (47%) is hatched.

The PTAA model has been tested on other glaciers (Tangborn, 1997, 1999) and has produced mass balance results that agree with independent measurements made by geodetic means. Detailed explanations of the model's key algorithms and the calibration procedure are provided in these earlier reports and duplication of these earlier explanations is not considered necessary here. However, a brief description of its application to the Langtang Glacier is included in the following section.

Model Explanation

Precipitation and temperature observations at Kathmandu are converted to precipitation (as snow or as rain) and ablation at each of the twenty-five 100 m altitude intervals of the glacier by algorithms that use 15 coefficients. By application of the simulated temperature and precipitation at each interval, the occurrence of snow or rain is determined; if the simulated temperature is 0° C or less, precipitation occurs as snow; if greater than 0° C, as rain.

It is proposed that the same physical laws operate on a glacier regardless of time or altitude, therefore the same set of coefficients is used for each day of the period and for each altitude interval. Thus over 100,000 values of each balance variable are calculated from a single set of coefficients. The lapse rates of both temperature and precipitation between Kathmandu and each altitude interval on the glacier are calculated by algorithms that use one or more of the 15 coefficients. Ablation is determined from the mean temperature and from the diurnal temperature range (an index of cloudiness and solar radiation). The mass balance at each altitude interval is calculated by the difference between snow accumulation and ablation (of both snow and ice), and the balance for the total glacier is found by integrating area and balance for all intervals. Both the snowline altitude and the zero-balance-altitude are determined each day by separate algorithms.

RESULTS

Simulated daily snowfall averaged for the period is shown in Fig. 5. Mean annual precipitation simulated for the entire glacier is 1.65 m (compared with 1.41 m at Kathmandu). Precipitation occurs as snowfall 73% (1.21 m), and as rain, 27% (0.44 m) of the time.

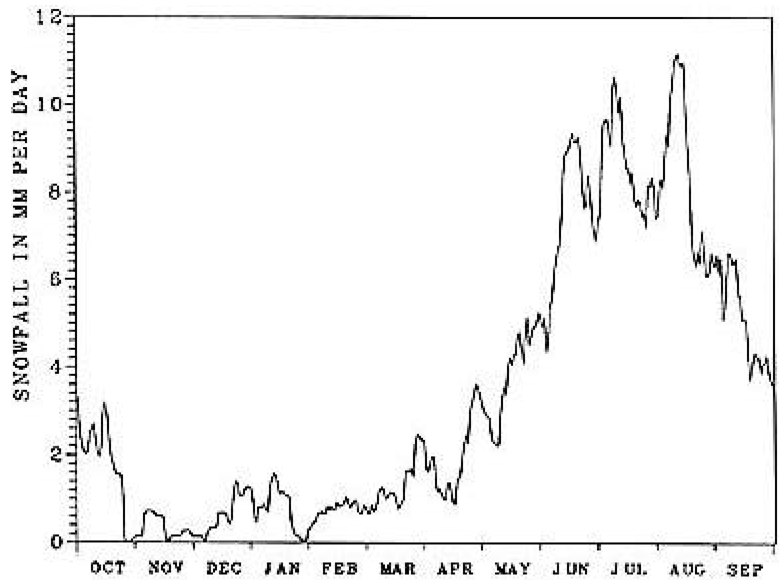

Fig. 5 The mean daily snowfall averaged over the glacier area and for the 1987-97 period. Precipitation occurs as snow when the mean daily temperature at the AA interval is 0° C or less. Approximately 75% of total annual precipitation as snow occurs during the summer monsoon season (June - September).

The extensive debris cover on this glacier complicates ablation measurements, both in the field and by model simulation. To account for the debris cover on the lower glacier in the model, a change was made in the ablation algorithm from previous model applications.

Considering only the radiation component of ablation:

$$A(i,z) = C_1 D(i) (C_2 (1-E(z)/S (i)) F(z) \qquad (1)$$

Where $A(i,z)$ is ablation due to solar radiation on day i and at altitude z, in mm per day, $D(i)$ is the diurnal temperature range on day i, $E(z)$ is the altitude interval z in meters, $S(i)$ is the snowline altitude in meters on day i, $F(z)$ is the fraction of altitude interval z covered by debris, and C_1, C_2 are coefficients determined by calibration.

The fraction of debris cover $F(z)$ is then the only change in this algorithm from previous PTAA model applications. When the factor $(1-E(z)/S)$ is less than zero, $A(i,z)$ is made equal to zero, therefore, ablation due to radiation derived from the temperature range is assumed to occur only below the snowline (high albedos at these altitudes precludes a significant direct radiation component of total ablation, however snowmelt still occurs due to indirect effects of radiation).

Measurements of ablation over debris-covered ice were conducted in 1995 on the Lirung Glacier, located 12 km west of Langtang Glacier (Rana *et al*, 1998). Results of these measurements, made at 4350 m altitude, from June 18-21, 1995 at 22 points with varying depths of debris thickness, are shown in Fig. 6. Measured ablation rates varied from a maximum of 450 mm per day for a debris thickness of 26 mm, to 160 mm per day when the thickness was 120 mm. The rate was 230 mm per day if no debris was present and the average rate for the 22 sites was 260 mm of ablation per day.

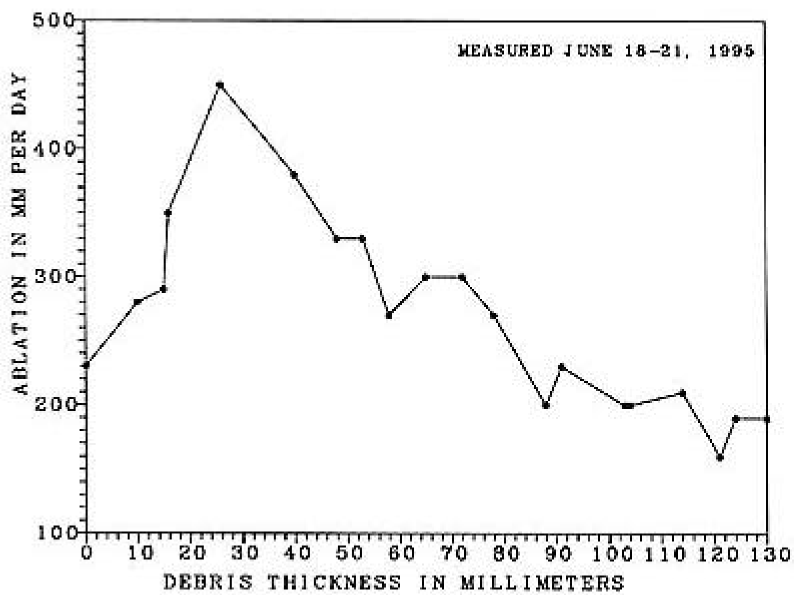

Fig. 6 Measured ablation at 22 points on the Lirung Glacier (at 4350 m altitude), for the June18-21 period. Maximum ablation occurred when the debris thickness was 260 mm.

Simulated ablation for the same period but at 200 m higher altitude (4550 m) on the Langtang Glacier averaged 113 mm per day (as the

Langtang Glacier terminus is at 4500 m, ablation could not be simulated at the same altitude as measurements on the Lirung Glacier). Taking into account the difference in altitude, and assuming 25% probable errors in both simulated and measured ablation rates, the two methods are in reasonable agreement. A comparison of measured and simulated daily ablation rates for 1995 is demonstrated in Fig. 7.

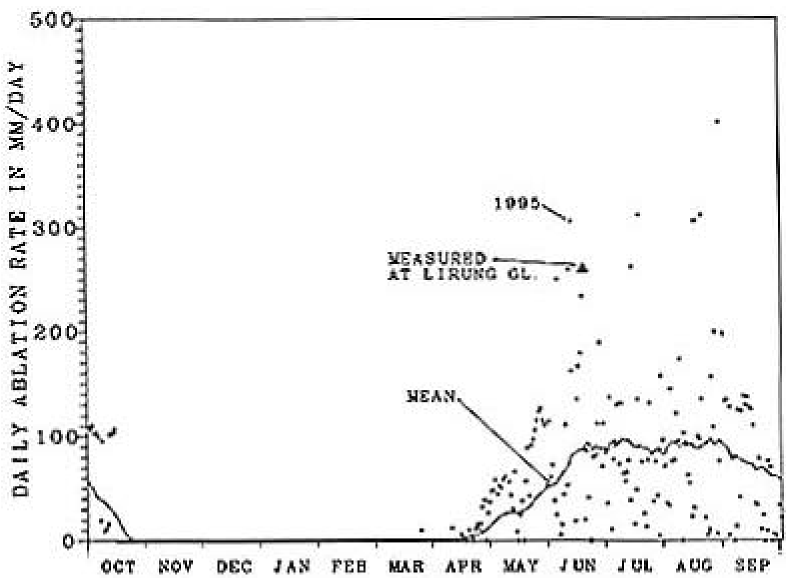

Fig. 7 Simulated daily ablation, averaged for the 1987-97 period (solid line), and for the 1995 water year (October 1994 - September 1995, dots). Measured ablation on nearby Lirung Glacier averaged for 22 points during the June18-21, 1995 period (large triangle) is shown for comparison with simulated ablation during the same time-period. The measured ablation is at 4350 m on the Lirung Glacier and the simulated is for 4550 m altitude on the Langtang Glacier (the lowest possible point).

Observations of the surface glacier melt rates are reported for Yala Glacier, a debris-free glacier located in the same valley, 7 km east of Langtang Glacier (Motoyama and Yamada, 1989). During a period from August 23 to September 3, 1987, at an altitude of 5100 m, ablation equaled 12.7 mm/°C/ day, and during September 3 to October 3, 1987 at 5300 m, it equaled 19.2 mm/°C/day. The PTAA model results for the same elevations and time-periods on the Langtang glacier gave 11.6 mm/°C/ day at 5100 m and 37mm/°C/ day at 5300 m. The reason for the large difference at 5300 m is unknown but could be caused by Yala Glacier being debris-free and Langtang Glacier having a significant debris-cover at this altitude. The values calibrated for the same period by HBV3- ETH model for lower elevations reasonably agree with measured ablation but for higher elevations the calibrated values are one-third of the observed. (Braun *et al*, 1993).

The daily balance for each interval is simply the difference between accumulated snowfall and ablation. The average cumulative daily balance over the total glacier throughout the year is shown in Fig. 8. The winter, summer and annual balances are found by averaging for the period of record the cumulative snowfall (winter balance), cumulative ablation (summer balance) and the resulting annual balance for each altitude interval (Fig. 9). ((Note: the terms winter and summer balance are not appropriate for Himalayan glaciers because much of the snow accumulation occurs during the summer monsoon season. Accumulation balance and ablation balance are considered more correct and will be used henceforth in this report). The cumulative daily balance for the 1987-97 period (Fig. 10) shows a significant difference in the time-distribution of balance from year to year. The average accumulation balance is 1.24 m(we), the ablation balance is -1.35, thus the mean annual balance for the 1987-97 period is -0.11 m(we).

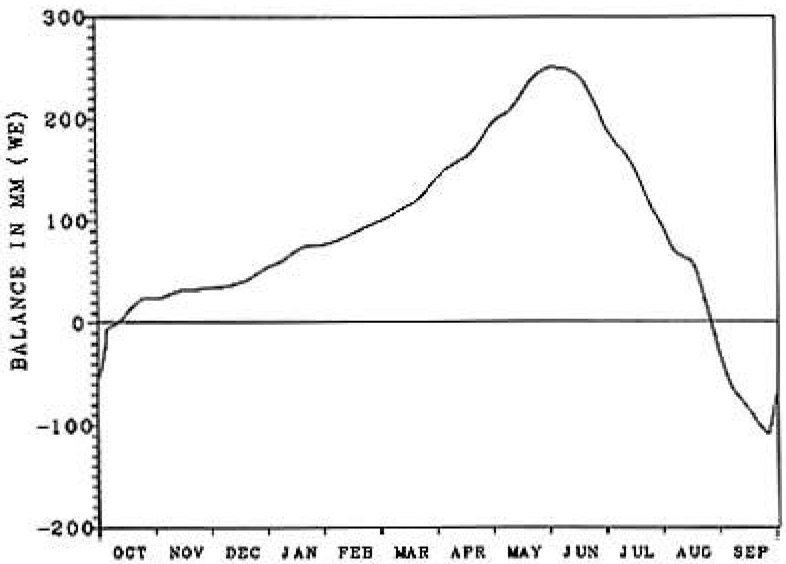

Fig. 8 The mean daily simulated mass balance averaged over the glacier for the 1987-97 period. The balance is equal to daily snowfall minus daily ablation, cumulated from October 1 - September 30 each year.

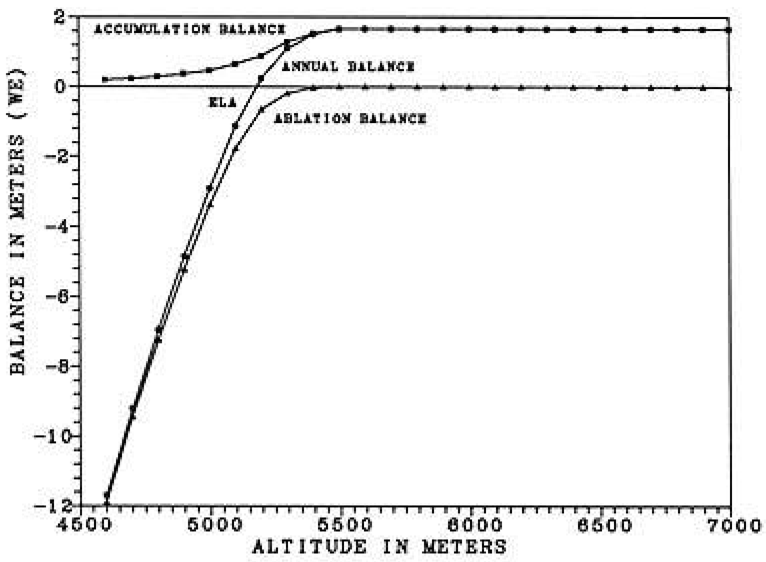

Fig. 9 The simulated accumulation (winter), ablation (summer) and annual balance as a function of altitude, averaged for the 1987-97 period. The simulated ablation rate at the terminus during the June 1 - September 30 season averages 98 mm per day. The ELA is approximately 5280 m.

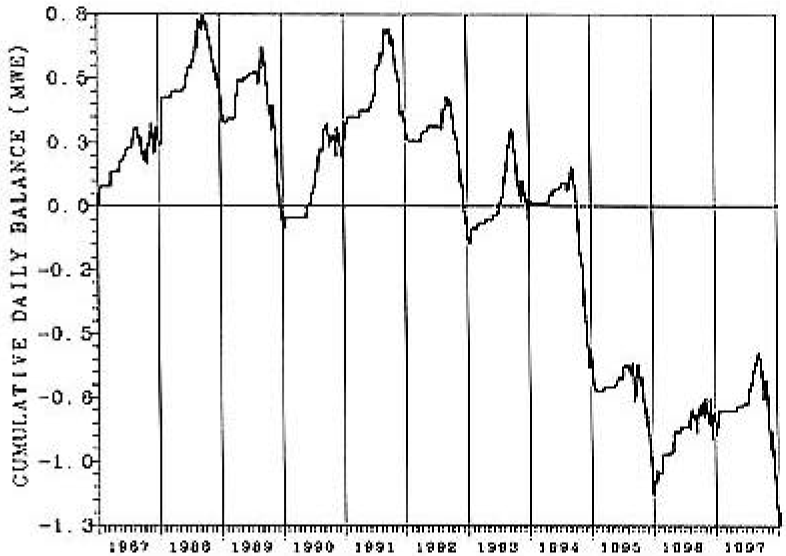

Fig. 10 The cumulative daily simulated balance for the 1987-97 period (4015 days). The mean annual balance for this period is -0.11 m (we).

Runoff from the glacier is the sum of precipitation as rain and total ablation of snow and ice. Internal water storage is likely a factor in daily runoff variations but is not taken into account in this preliminary study. The mean daily and maximum simulated runoff for the total glacier, shown in Fig. 11, is similar in magnitude and variation as observed runoff for the Lirung Glacier basin (Rana *et al*, 1997). Mean annual simulated runoff is 1.76 m; precipitation accounts for 94 percent and 6 percent is derived from the loss in glacier mass. The mean maximum simulated discharge is approximately 20 m^3 per second and usually occurs in early August. The mean simulated discharge for the year is 4.3 m^3 per second.

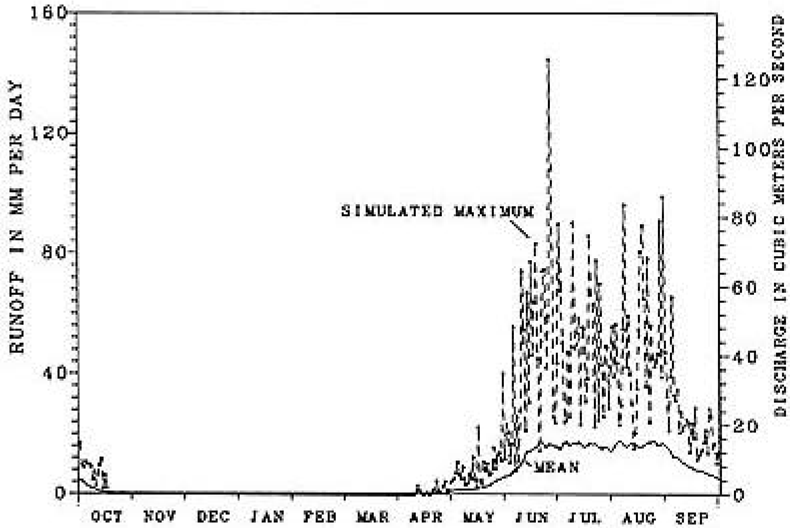

Fig. 11 Simulated runoff in millimeters per day from the glacier is the sum of total ablation and precipitation as rain averaged over the total glacier area (solid line) and the simulated maximum (dashed line). The storage and release of water from internal storage may be a significant factor but is not considered here. Discharge in cubic meters per second (right scale) is the daily mean and maximum for the period of record.

CONCLUSIONS

These preliminary results indicate that realistic mass balance and runoff can be simulated for the Langtang Glacier using meteorological observations at Kathmandu and the glacier's AA profile. The agreement between measured and simulated ablation is within reasonable error limits. Further investigation by the application of the PTAA model to this glacier to calculate the mass and energy exchange at a large number of surface facets may yield fruitful results regarding the effect of debris-cover on glacier mass balance and runoff.

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