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MASS-BALANCE STUDIES OF GARA GLACIER*

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Abstract. The Gara Glacier, a north-facing valley glacier situated in the western Himalaya, was selected to be part of the study undertaken by India in connection with the International Hydrological Decade. This paper deals with the procedure adopted and the results obtained for mass-balance assessment over a period of one year between September 1974 and September 1975. The glacier has recorded a positive net balance of the order of 2.48×10^6 m³ in terms of water equivalent.

Résumé. *Études de bilans de masse sur le Gara Glacier*. On a choisi le Gara Glacier, un glacier de vallée exposé au Nord dans l'Ouest de l'Himalaya, comme objet d'études entreprises par l'Inde en relation avec le programme de la Décennie Hydrologique Internationale. Ce papier décrit la méthode employée et les résultats obtenus pour estimer le bilan de masse sur une période d'un an de septembre 1974 à septembre 1975. Le glacier a enregistré un bilan net positif de l'ordre de $2{,}48 \times 10^6$ m³ d'équivalent en eau.

Zusammenfassung. *Studien zum Massenhaushalt des Gara Glacier*. Der Gara Glacier, ein nordexponierter Talgletscher im West-Himalaya, wurde als Teilprojekt der indischen Untersuchungen im Rahmen der Int. Hydrologischen Dekade ausgewählt. Hier wird über das angewandte Verfahren und über die Ergebnisse bei der Abschätzung des Massenhaushaltes über den Zeitraum eines Jahres zwischen September 1974 und September 1975 berichtet. Der Gletscher wies eine positive Nettobilanz in der Grössenordnung von $2{,}48 \times 10^6$ m³ Wasseräquivalent auf.

Introduction

Gara Glacier is located in the Kinnaur District of Himachal Pradesh, India, in the main Himalayan range, about 130 km east of Simla. The glacier has a very high winter precipitation with a seasonal snow accumulation of 6 m and above. It receives very little precipitation during the monsoon period.

The glacier occupies the Gara Khad basin, a fourth-order tributary of the River Indus, with an overall area of 24.50 km² of which 24% is glacier-covered. The basin originates from the northern side of an east–west trending ridge which marks the watershed between the Baspa valley in the south and Tidong Khad in the north, and extends down up to its confluence with the Tidong Khad.

Gara Glacier is a small valley glacier, originating at an altitude of 5 600 m a.s.l. and terminates at an altitude of 4 710 m a.s.l. The glacier is 6 km long and 1.5 km wide at its broadest, and has an average gradient of 1 in 7 in a slightly serpentine, north-easterly direction. The longitudinal profile of the glacier is characterized by three flat regions separated by steeper gradients.

The glacier is fed, at present, by three ice bodies draining from independent accumulation areas. These independent bodies coalesce together into a broad basin of area 2.5 km² from whence a single tongue flows as a single unit. Independent streams are, however, easily discernable within this tongue, as their boundaries are well marked by longitudinal septa.

The main active ice stream of Gara Glacier (A of Fig. 1), which forms the eastern part of the ice body, bears at its head a well-developed cirque covering an area of 1 km². This cirque is characterized by the presence of sharply serrated ridges along its southern and eastern side and a prominent glacial horn—Daboling peak 6 054 m—marks its western limit. A well-developed bergschrund, about a metre wide, exists at the base of the serrated ridge at the head of this cirque.

At the northern base of the peak Daboling, a smaller cirque of area 0.03 km² exists and forms the main accumulation area for the western feeder of the glacier (C of Fig. 1). Yet another smaller feeder, mainly avalanche fed, starts from the north-eastern face of the same peak.

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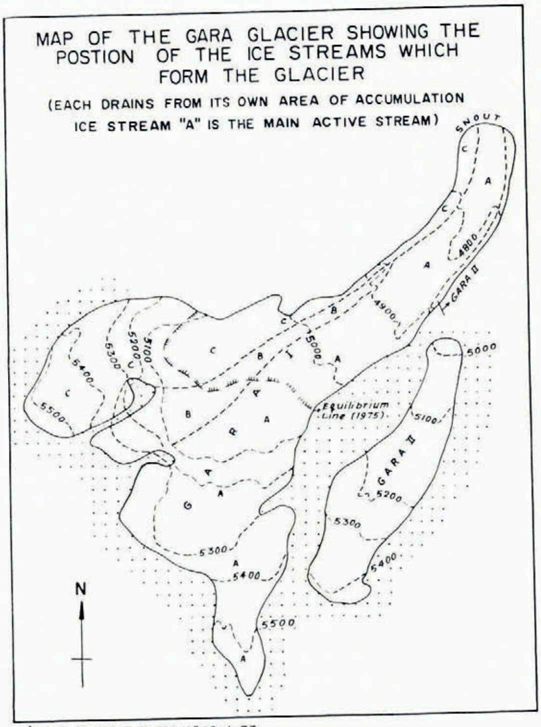

Fig. 1. Map of Gara Glacier showing the position of the ice streams which form the glacier.

A small ice body with an independent accumulation area exists east of the main glacier. This ice body, which must at one time have been a feeder to the main glacier, is now disconnected from it and at present supports a distinct snout of its own. This ice body has been referred to by the present workers as "Gara II" in the absence of any name given to it on Survey of India maps.

Glaciological methods

Two methods were adopted for assessing the mass balance: (1) subtracting the total accumulation, in terms of water equivalent, at the end of the accumulation season (April) from total ablation at the end of the ablation season (September); this necessitated a visit to the glacier during April 1975 for observations. (2) Subtracting the values of net accumulation from net ablation *vis-à-vis* the glacier surface of the previous year. Observations for this have been in hand since June 1974.

The procedures adopted for the measurements and calculation are as given by Østrem and Stanley (1966) and Hoinkes and Rudolph (1962).

Winter balance

A winter-balance study to assess the total accumulation of the snow cover on the glacier surface at the end of the accumulation season was carried out during the month of April 1975. The procedure adopted was to take soundings followed by digging pits and trenches at selected intervals to assess: (1) accumulation and (2) density of the accumulated snow.

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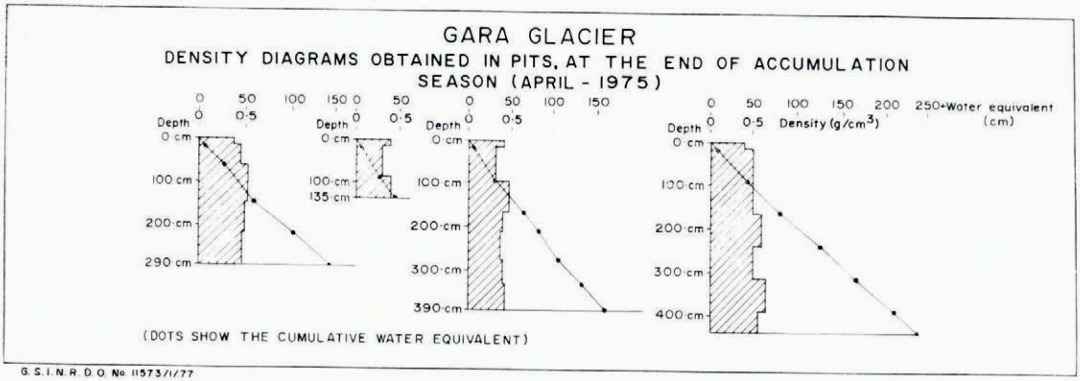

Fig. 2. Density diagrams obtained in pits, at the end of accumulation season (April 1975).

Sounding along selected lines was carried out with the help of avalanche rods. The rods were inserted into the snow cover and the depth up to which the rods could enter under a normal pressure was taken as the seasonal thickness of the accumulated snow. Pits were excavated at some of the sounding spots to confirm the total accumulation (Fig. 2) and also to measure the density of the accumulated snow. The pits were excavated by ordinary shovels, in a box pattern, with one side cut more or less evenly for snow density sampling. Sampling began when the pit had touched what was presumed to be the last year's

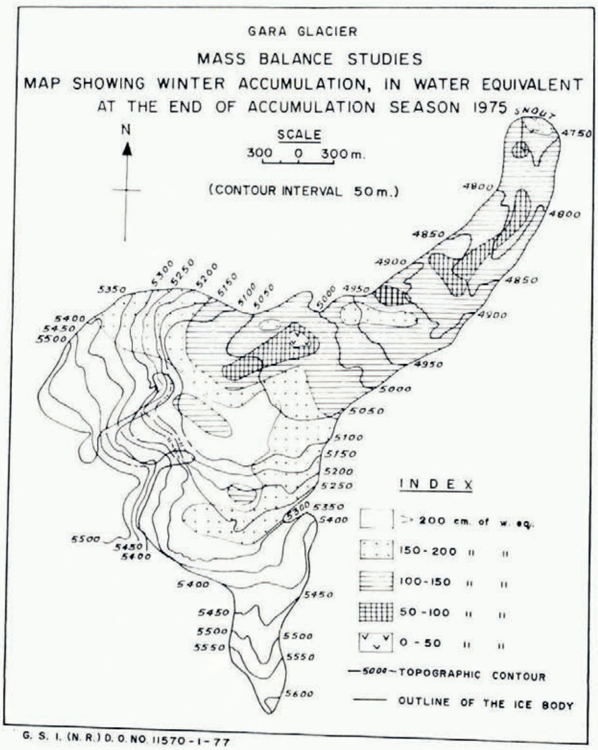

Fig. 3. Map showing winter accumulation, in water equivalent, at the end of accumulation season 1975.

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TABLE I. GARA GLACIER MASS-BALANCE ESTIMATES IN WATER EQUIVALENT (BALANCE YEAR 1974–75)

Winter balance

	0–50 cm		50–100 cm		100–150 cm		150–200 cm		200–300 cm		*Total*	
Elevation m	*Area* km^2	*Volume* 10^6 m^3	*Area* km^2	*Volume* 10^6 m^3	*Area* km^2	*Volume* 10^6 m^3	*Area* km^2	*Volume* 10^6 m^3	*Area* km^2	*Volume* 10^6 m^3	*Area* km^2	*Volume* 10^6 m^3
5 600–									0.011	0.027	0.011	0.027
5 550–5 600									0.067	0.167	0.067	0.167
5 500–5 550									0.157	0.392	0.157	0.392
5 450–5 500									0.180	0.450	0.180	0.450
5 400–5 450							0.001	0.002	0.315	0.787	0.316	0.789
5 350–5 400							0.045	0.078	0.315	0.787	0.360	0.865
5 300–5 350							0.045	0.078	0.202	0.505	0.247	0.583
5 250–5 300							0.157	0.274	0.225	0.562	0.382	0.836
5 200–5 250					0.022	0.027	0.157	0.274	0.090	0.225	0.269	0.526
5 150–5 200					0.004	0.005	0.135	0.236	0.090	0.225	0.229	0.466
5 100–5 150					0.011	0.013	0.135	0.236	0.067	0.167	0.213	0.416
5 050–5 100			0.045	0.033	0.247	0.308	0.225	0.393	0.225	0.562	0.742	1.296
5 000–5 050	0.022	0.005	0.090	0.067	0.382	0.477	0.135	0.236			0.629	0.785
4 950–5 000					0.135	0.168	0.022	0.038			0.157	0.206
4 900–4 950			0.033	0.024	0.225	0.281	0.045	0.078			0.303	0.383
4 850–4 900			0.045	0.033	0.225	0.281					0.270	0.314
4 800–4 850			0.045	0.033	0.247	0.308					0.292	0.341
4 750–4 800			0.045	0.033	0.225	0.281					0.270	0.314
4 700–4 750			0.002	0.0001	0.045	0.056	0.033	0.057	0.006	0.015	0.084	0.128
Totals	0.022	0.005	0.303	0.223	1.768	2.205	1.135	1.980	1.950	4.871	5.178	9.284

Summer balance

	0–50 cm		50–100 cm		100–150 cm		150–200 cm		200–250 cm		250–300 cm		300–350 cm		*Total*	
Elevation m	*Area* km^2	*Volume* 10^6 m^3	*Area* km^2	*Volume* 10^6 m^3	*Area* km^2	*Volume* 10^6 m^3	*Area* km^2	*Volume* 10^6 m^3	*Area* km^2	*Volume* 10^6 m^3	*Area* km^2	*Volume* 10^6 m^3	*Area* km^2	*Volume* 10^6 m^3	*Area* km^2	*Volume* 10^6 m^3
5 600–	0.011	0.002													0.011	0.002
5 550–5 600	0.067	0.016													0.067	0.016
5 500–5 550	0.157	0.039													0.157	0.039
5 450–5 500	0.180	0.045													0.180	0.045
5 400–5 450	0.316	0.079													0.316	0.079
5 350–5 400	0.360	0.090													0.360	0.090
5 300–5 350	0.224	0.056			0.023	0.028									0.247	0.084
5 250–5 300	0.355	0.088	0.015	0.011	0.012	0.015									0.382	0.114
5 200–5 250	0.084	0.021	0.056	0.042	0.129	0.161									0.269	0.224
5 150–5 200	0.033	0.008	0.032	0.024	0.132	0.165	0.032	0.056							0.229	0.253
5 100–5 150	0.019	0.004	0.004	0.003	0.172	0.215	0.018	0.031							0.213	0.253
5 050–5 100	0.033	0.008	0.046	0.034	0.345	0.431	0.318	0.556							0.742	1.029
5 000–5 050					0.153	0.191	0.167	0.292	0.309	0.695					0.629	1.178
4 950–5 000									0.067	0.150	0.090	0.247			0.157	0.397
4 900–4 950					0.022	0.027	0.084	0.147	0.002	0.004	0.159	0.536			0.303	0.714
4 850–4 900							0.214	0.374	0.045	0.101	0.011	0.030			0.270	0.505
4 800–4 850							0.067	0.117	0.225	0.506					0.292	0.623
4 750–4 800							0.079	0.138	0.135	0.303	0.056	0.154			0.270	0.595
4 700–4 750									0.071	0.159	0.011	0.030	0.002	0.006	0.084	0.195
Totals	1.839	0.456	0.153	0.114	0.988	1.233	0.979	1.711	0.854	1.918	0.363	0.997	0.002	0.006	5.178	6.435

Mass balance

Elevation m	*Area* km^2	*Accumulation* 10^6 m^3	*Ablation* 10^6 m^3	*Net balance* 10^6 m^3
5 600–	0.011	0.027	0.002	+0.025
5 550–5 600	0.067	0.167	0.016	+0.151
5 500–5 550	0.157	0.392	0.039	+0.353
5 450–5 500	0.180	0.450	0.045	+0.405
5 400–5 450	0.316	0.789	0.079	+0.710
5 350–5 400	0.360	0.865	0.090	+0.775
5 300–5 350	0.247	0.583	0.084	+0.499
5 250–5 300	0.382	0.836	0.114	+0.722
5 200–5 250	0.269	0.526	0.224	+0.302
5 150–5 200	0.229	0.466	0.253	+0.213
5 100–5 150	0.213	0.416	0.253	+0.163
5 050–5 100	0.742	1.296	1.029	+0.267
5 000–5 050	0.629	0.785	1.178	−0.393
4 950–5 000	0.157	0.206	0.397	−0.191
4 900–4 950	0.303	0.383	0.714	−0.331
4 850–4 900	0.270	0.314	0.505	−0.191
4 800–4 850	0.292	0.341	0.623	−0.282
4 750–4 800	0.270	0.314	0.595	−0.281
4 700–4 750	0.084	0.128	0.195	−0.067
Totals	5.178	9.284	6.435	+2.849

accumulation surface: a thick layer of superimposed ice which could not be dug through using shovels.

Density measurements were carried out using a brass sampler of known volume. Samples for density measurement were collected by pressing the brass tube gently into the snow or firn and the sample so collected was weighed on a 5 kg balance. Density was calculated by dividing the weight by the known volume and conversion into water equivalent was done by multiplying the density by the length of the sample.

The data so obtained were plotted on a map of the glacier on 1 : 15 000 scale and the iso-lines drawn at selected intervals of 50 cm of water equivalent. The area bounded by the iso-lines was shadowed (Fig. 3). A chart was then prepared to show the accumulation for every 50 m of altitude (Table I). For the evaluation of the accumulation above 5 200 m a.s.l., the accumulation values recorded at the close of the ablation season (September 1975) were utilized and it was presumed, for the purposes of calculation, that there had been no ablation in between. The gross value of accumulation so obtained over the entire glacier, amounts to some 9.28×10^6 m^3 water equivalent for the period October 1974 to April 1975.

Summer balance

To evaluate the summer-balance values, i.e. the ablation the glacier had undergone *vis-à-vis* the accumulation at the end of April, use had to be made of the network of stakes fixed over the glacier and also pits dug in the accumulation zone (Fig. 4).

Insertion of stakes on the Gara Glacier had begun with the investigation of mass balance in the month of June 1974. The stakes were fixed with the help of a thermal drill of 500 W run by a petrol engine. Most of the stakes have been inserted up to a depth of 6 m in the ablation zone and up to 2 m in the accumulation zone. In the upper reaches of the glacier, where the firn layers were comparatively soft, the stakes were inserted with the help of a hand auger. The stakes were kept under constant observation, except during the winter months when they were buried under the winter snow, to record surface ablation. Density checks were carried out at three to four spots every day, close to the stakes, in the ablation zone and within the pits excavated in the accumulation zone. In the ablation zone the density measurements were carried out by cutting blocks of ice of known dimensions with the help of a steel hack-saw. The blocks thus obtained were weighed and the density calculated by dividing the weight by volume. The ablation data *vis-à-vis* the accumulation surface observed in April (the winter balance) was thus calculated at the site of each of the stakes as well as the pits and was plotted on a map of the Gara Glacier. Iso-lines were drawn at intervals of 50 cm of water equivalent and the map shaded accordingly (Fig. 5). The ablation values were calculated for every 50 m

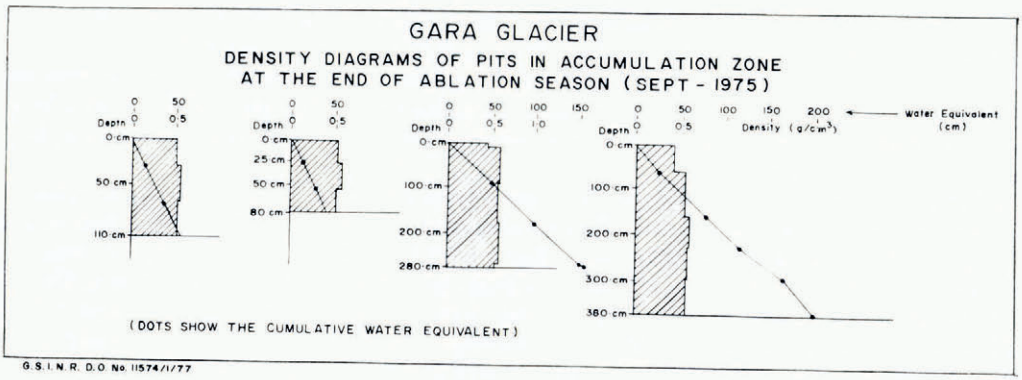

Fig. 4. Density diagrams of pits in accumulation zone at the end of ablation season (September 1975).

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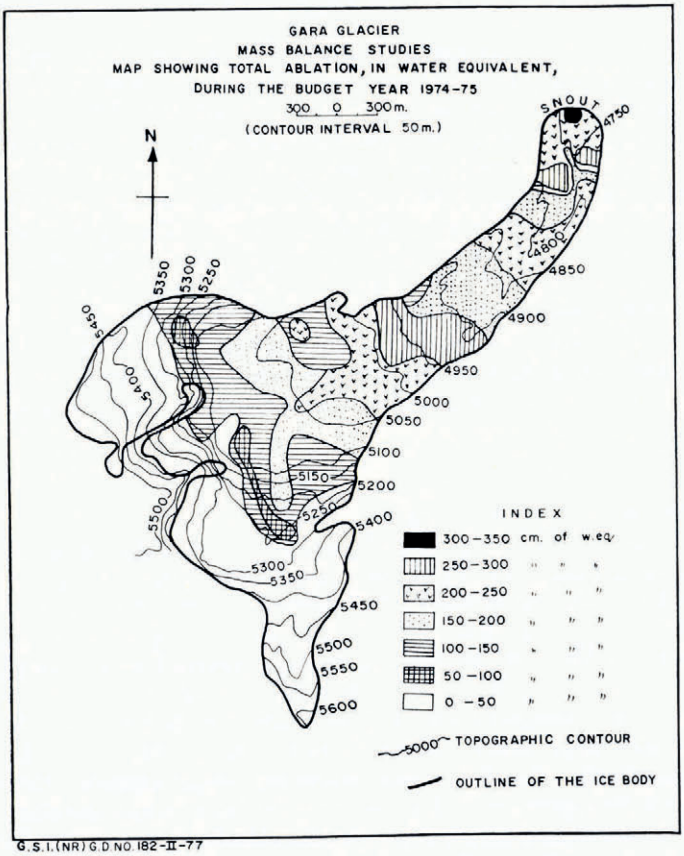

Fig. 5. Map showing total ablation, in water equivalent, during the balance year 1974–75.

of altitude and the gross ablation value of 6.43×10^6 m^3 arrived at (Table I). The net balance value was obtained by subtracting the ablation value from the accumulation value which yields 2.85×10^6 m^3 water equivalent. It is thus seen that the Gara Glacier had a positive net balance for the period September 1974–September 1975.

To corroborate the results so obtained, the mass balance values were also evaluated by the alternative method, i.e. by calculating the net accumulation and the net ablation *vis-à-vis* the glacier surface of September 1974. These data were computed from the accumulation and ablation as recorded by the network of stakes and also by digging pits in the accumulation zone. From the data so computed, the mean level of the equilibrium line was found to be at 5 050 m a.s.l. for the year 1975.

Within the accumulation and ablation areas thus demarcated, corresponding values of accumulation and ablation, in terms of water equivalent, were plotted. Iso-lines were drawn at intervals of 25 cm of water equivalent (Figs 7 and 8) and the areas shaded accordingly. The accumulation and the ablation values, within the respective areas, were then computed by multiplying the area between a particular pair of iso-lines with the average water-equivalent values within the corresponding shaded area. The net values for accumulation and ablation thus arrived at (inset on Figs 7 and 8) were found to be 4.38×10^6 m^3 and 1.88×10^6 m^3 respectively. In other words a positive budget of the order of 2.50×10^6 m^3.

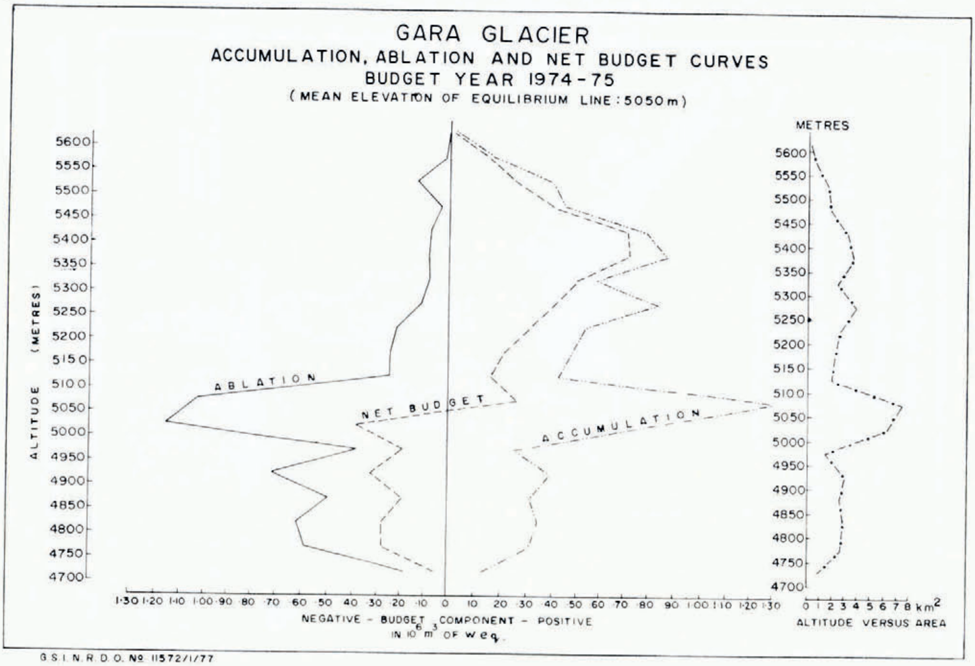

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Fig. 6. Accumulation, ablation and net balance curves.

Yet another factor which has been taken into consideration is the ablation along the snout front. A comparative study of the 1974 and 1975 snout front of the glacier has revealed that an estimated 14 400 m^3 of ice have melted away along the front releasing 0.013×10^6 m^3 in terms of water equivalent. This value has been deducted from the balance values obtained by either of the described methods

$$2.85 \times 10^6 \text{ m}^3 - 0.013 \times 10^6 \text{ m}^3 = 2.83 \times 10^6 \text{ m}^3,$$
$$2.50 \times 10^6 \text{ m}^3 - 0.013 \times 10^6 \text{ m}^3 = 2.48 \times 10^6 \text{ m}^3,$$

which, however, continues to be on the positive side.

Error estimation

The percentage difference between the two values comes to 3.79%, which is well within the accepted limits as an average difference up to 3.88% is considered normal. The formulae used in calculating the difference is the one adopted by Mokievskiy-Zubok (1974)

$$E_{\text{sp}} = \frac{(b_{\text{n}_1} - b_{\text{n}_2})}{b_{\text{w}}} \times 100 = \frac{2.83 \times 10^6 \text{ m}^3 - 2.48 \times 10^6 \text{ m}^3 \times 100}{9.28 \times 10^6 \text{ m}^3} = 3.79\%,$$

where E_{sp} is the difference expressed as a percentage, b_{n_1} the net balance using the first method, b_{n_2} the net balance using the alternative method, and b_{w} the winter balance.

Procedural handicaps

Evaluation of the accumulation data, in the case of the glaciers in the Himalaya, is a formidable task as the accumulation zone ranges in altitude above 5 000 m a.s.l., and exhibits a rugged ice topography with limited accessibility. Because of crevasses, it is not, at times, possible to insert the stakes where these should have been in the interests of data recording.

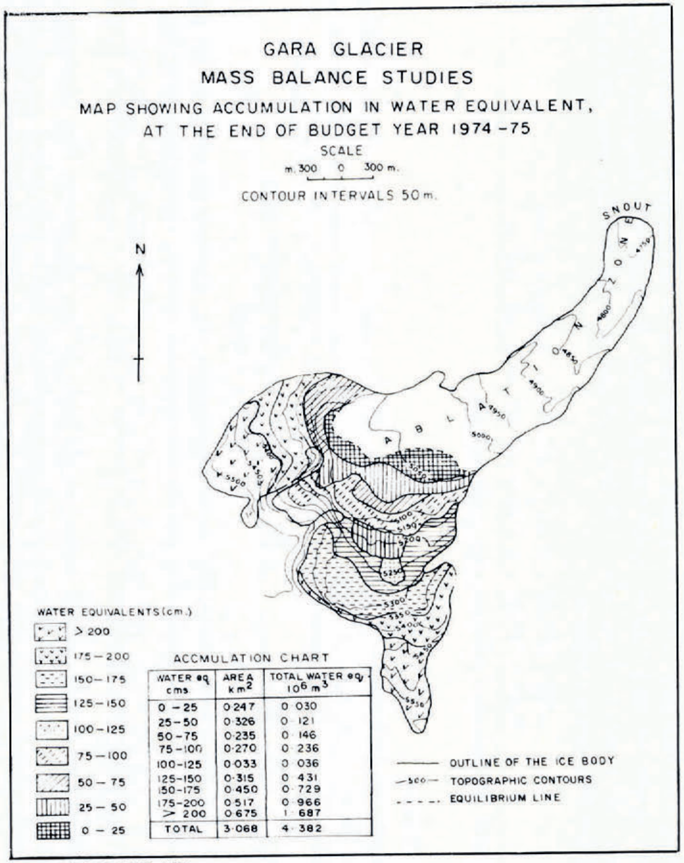

Fig. 7. Map showing accumulation, in water equivalent, at the end of balance year 1974–75.

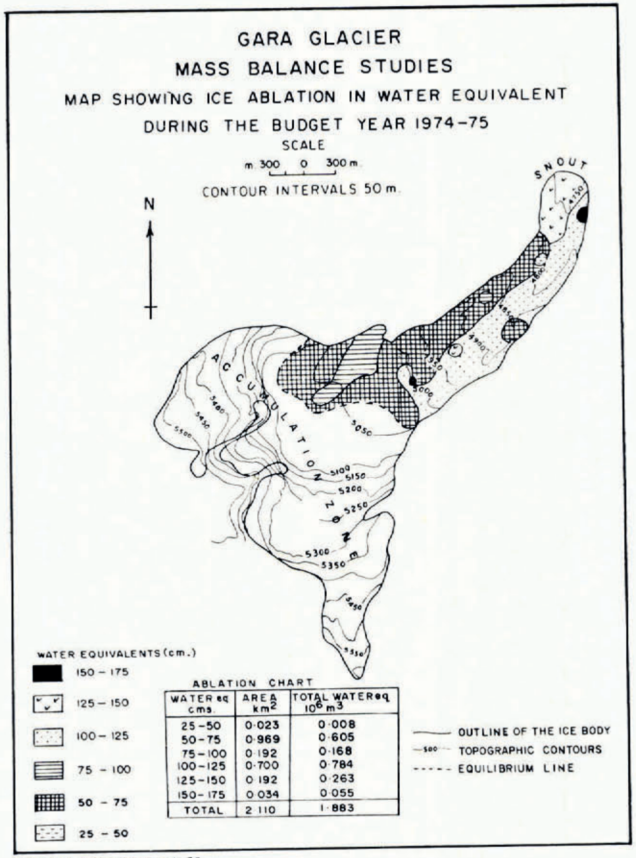

Fig. 8. Map showing ice ablation, in water equivalent, during the budget year 1974–75.

In fact, the studies in the accumulation zone had to be restricted to areas which are safe from avalanches and other hazards. Consequently in assessing the accumulation values, a few inaccuracies do enter, no matter how careful one otherwise is in the observations.

In calculating the annual accumulation at the end of the ablation season, knowledge of the previous year's glacier surface is essential. As no such information was available, indirect presumptions had to be relied upon for the determination of the last year's firn surface. In the present case a thick layer of superimposed ice which could neither be broken through nor dug through by an ordinary shovel, and which was encountered at various depths in all the pits excavated in the accumulation zone, was considered to be the top of the previous years firn surface. This assumption was supported by: (1) the correlation with the sections exposed in the crevasses near by and (2) density distribution of the accumulated snow in the pits.

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