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DETERMINATION OF SNOW AND ICE MELT FACTORS IN THE HIMALAYAN REGION THROUGH FIELD INVESTIGATIONS

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Preface

A substantial amount of streamflow in the Himalayan rivers is derived from the snow and glacier melt runoff. Detailed climatic data is required for the snow and glacier melt estimation using energy balance approach, but availability of such data is very poor in the Himalayas. Therefore, snow melt and glacier melt studies are based on the temperature index approach in the Himalayan region. The degree-day factor is a very important factor because of its practical importance in estimating the ablation using temperature data. Thus, determination of the degree-day factors for snow and ice becomes very important for computing the depth of snow and ice melt using air temperature data. No attempts have been made earlier to determine these factors for the Himalayan region. In the present study, degree-day factors for snow and ice were computed over Dokriani glacier at an altitude of about 4000m in the Garhwal Himalayas through field experiments. Effect of natural dusting on both degree-day factors was also examined.

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(S. M. Seth)

Director

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Abstract

Information on the degree-day factor for snow and ice is required for the estimation of snow and ice melt runoff from a glacierized basin. In the present study, degree-day factor for snow and ice are computed over Dokriani glacier at an altitude of about 4000m in the Garhwal Himalayas. Effect of natural dusting on both degree-day factors is also examined. For this purpose, natural dust available at the experiment site was uniformly spread over the surfaces of snow and ice blocks to form a 2 mm thick layer of it. The melt runoff from the snow and ice blocks along with air temperature at 2 m above the surface have been observed. Mean degree-day factor for clean and dusted snow blocks are computed to be 5.75 and 6.41 mm°C^{-1} d^{-1}, respectively, whereas for clean ice and dusted ice the value of this factor was obtained to be 7.33 and 7.97 mm°C^{-1} d^{-1}, respectively. Mean daily melt factors for dusted snow and dusted ice are always found higher than corresponding dust free snow and ice blocks. The average maximum hourly value of melt factor for the clean and dusted snow blocks were obtained to be 0.706 and 0.871 mm°C^{-1} hr^{-1}, respectively, while minimum value was zero for all the cases. In the case of ice, the average maximum hourly ice melt factor was observed to be 0.919 and 1.057, respectively. Maximum hourly value of melt factor occurred at about 12 hours for both blocks. A comparison of degree-day factors for snow and ice is made with already available information in literature.

1.0 INTRODUCTION

The melt runoff from a glacierized basin is an over all result of many different processes of heat transfer to the snow and ice surfaces. The quantity of melt water is also dependent upon the condition of the snow and ice. As a consequence, the determination of snow and ice melt runoff is complex and certain simplifying assumptions are used in the practical computation of snow and ice melt. Temperature index or the degree-day approach is generally considered to be the best index of the heat transfer processes associated with melting of snow and ice because temperature index approach often gives melt estimates comparable to those determined from a detailed evaluation of the various components in the energy balance (U. S. Army Corps of Engineers, 1971; Anderson, 1973). Moreover, air temperatures are the only most readily available data other than precipitation in the high altitude regions. For these reasons, temperature index is most widely used method of snow and ice melt computation. However, no single universally applicable temperature index of snow and ice melt estimation exits, but whenever a temperature index approach is used, knowledge on the snow and ice melt factor is required.

An appreciable quantity of the flow of Himalayan rivers is derived from the snow and glacier melt runoff (Singh et al., 1995). Availability of the detailed climatic data required for the snow and glacier melt runoff modelling using energy balance approach, is very poor in the Himalayas. All the hydrological studies are based on the temperature index approach in the Himalayan region. For a proper exploitation of water available as snow and ice reservoirs and its full utilisation, a knowledge of several parameters associated with melting of snow and ice is needed. The important parameters are snow melt factor and ice melt factor or the degree-day factors for snow and ice. The degree-day factor is a very important factor because of its practical importance in estimating the ablation using temperature data. The degree-day factor involves a simplification of complex processes that are more properly described by the energy exchange processes between surface of snow/ice and atmospheric boundary layer. The first application of degree-day approach was made by Finsterwalder and Schunk (1887) in the Alps and since then this approach is being used all over the world for estimation of snow and ice melt runoff. These parameter are used to convert the degree-days to snowmelt or ice melt expressed in depth of water. It is given in the following form:

For snow

$$M = D_{sf}\,(T_a - T_o) \qquad (1)$$

For ice

$$M = D_{if}\,(T_a - T_o) \qquad (2)$$

where M = depth of melt water (mm/unit time), T_a = mean air temperature (°C); T_o = base temperature (0°C); and D_{sf} = snow melt factor (mm/(°C. unit time)), D_{if} = ice melt factor (mm/(°C. unit time)). When the unit time is one day, then melt factor is termed as degree-day factor. The value of degree-day factor varies with melt period because of changes in snow properties which influence the melting process. It is expected that degree-day factor for ice has a little variation during a season as compared to snow because ice properties do not change very significantly in a season. In spite of importance of daily snow melt factors or degree-day factors for snow and ice for computation of melting from snow and ice covered areas, as such no information is available on these factors for any Himalayan basin at any time of the year (Singh and Kumar, 1996). However, 6-hour melt factor was determined from the isolated snow blocks (Singh et al., 1995). Further, all the simulation or forecasting of snow and glacier melt runoff studies are carried out on the daily basis. Hourly simulation have not been carried out for any basin simply because no hourly data are available. Therefore, values of degree-day factor for snow and ice are more useful for the Himalayan basins in comparison to the hourly or 6-hourly values. Consequently, studies were planned and carried out to estimate degree-day factor for snow. No study was carried out to estimate degree-day factor for ice. It is not known as to how the dusting of ice surface affects the melting of ice. However, it is expected that degree-day factor for ice would be higher than that for snow because of lower albedo for the ice surfaces. A comparison of the previously determined value of degree-day factor for snow is made with the values obtained in this study. In the present study degree-day factors for both snow and ice are determined at the Dokriani glacier. Hourly melt factors for snow and ice are also calculated for this period and discussed. Degree-day factors obtained for snow and ice, which were obtained under the same environment conditions, were compared. Such studies at present are not available for the Himalayas

2.0 REVIEW OF DEGREE-DAY FACTORS FOR SNOW AND ICE

The values of degree-day factors reported by various investigators for snow and ice for various glaciers are given in Table 1. As such there is a broad agreement in degree-day factors for ice except for a high value of 13.8 mm $d^{-1\circ}C^{1}$ found in Spitsbergen by Schytt (1964). The degree-day factor for snow is lower than that of ice. Braithwaite (1995) estimated degree day factors for snow and ice using energy-balance model and found that the degree-day factor for snow is less than half that for ice. The degree-day factors vary with mean temperature, albedo and turbulence and a better understanding of these parameters contribute to remaining uncertainties of degree-day factor.

Table 1: The degree-day factors for snow and ice on various glaciers or used by various investigators (mm °C^{-1} d^{-1})

Degree-day factor for Snow	Degree-day factor for Ice	Location	References
-	5.0-7.0	Swiss glaciers	Kasser (1959)
-	13.8	Spitsbergen	Schytt (1964)
-	6.3	Store Supphellebre	Orheim (1970)
3 - 5	8.0		Borovikova et al.(1972)
5.4	-	Gr. Aletschgletscher	Lang et al. (1977)
-	5.5± 2.3	Norway	Braithwaite (1977)
-	6.3±1.0	Arctic Canada	Braithwaite (1981)
2.5	7.2	Nordbogletscher	Braithwaite and Olesen (1988)
3.0	6.0	Franz Josef Glacier	Woo and Fitzharris (1992)
5.7	7.7	Satujokull	Jóhannesson et al. (1995)
4.4	6.4	Nigardsbreen	Jóhannesson et al. (1995)
4.5	6.0	Alfotbreen	Laumann and Reeh (1993)
4.0	5.5	Nigardsbreen	Laumann and Reeh (1993)
3.5	5.5	Hellstugubreen	Laumann and Reeh (1993)
5.94	-	Dokriani glacier (Himalayas)	Singh and Kumar (1996)

Braithwaite and Olesen (1993) determined degree-day factors at Qamanârssûp sermia, West Greenland, and computed for each month and season by dividing the ablation by the positive degree days for the corresponding period (Table 2). It was found that for this area, degree-day factors for the summer months (June, July and August) were almost similar, with a maximum value for the month of July. It is understood that Fohn-type weather involves high temperatures and high wind speeds, resulting in sensible heat fluxes. Under such conditions high degree-day factors are possible (Braithwaite and Olesen, 1990). This study shows that the degree-day factor varies with season, but usually it is treated as a constant throughout the melt season.

Table 2: Degree-day factors at Qamanârssûp sermia, west Greenland (mm°C^{-1} d^{-1})

Period	1979-80	1980-81	1981-82	1982-83	1983-84	1984-85	1985-86	Mean
Sept. - May	8.95	10.94	7.84	13.67	6.61	10.40	7.60	9.43
Jun	6.38	7.12	7.23	8.25	7.41	8.76	6.19	7.33
Jul	6.62	8.16	8.62	9.07	7.46	7.85	7.98	7.96
Aug	5.96	6.32	8.49	7.31	7.53	7.67	7.96	7.32
Sept.-Aug	6.74	7.89	8.08	9.19	7.36	8.53	7.63	7.92

2.1 Augmentation of snow and ice melt under dusting conditions

Albedo governs the amount of radiant energy absorbed by a snow and ice surfaces and hence is very important for determining the rate of melting. The blackening of snow surface reduces the albedo of snow significantly. Only few studies are reported in literature pertaining to the accelerated melting of snowpack due to dusting. The first experiment on artificial dusting of the glaciers was conducted by Prof. G. A. Avsiuk between 1950 and 1952. Four series of experiments were carried out, each taking three or four days. It was concluded that most efficient melting occurs when the input of coal dust was between 5 and 10 g/m^2. Dusting at this recommended rates causes the albedo of the young firn and snow surfaces to decrease on the average to 0.25-0.30, old firn to 0.15-0.20 and ice to 0.07-0.10. At the same time, melting in comparison with dust free surface increases 3 to 4 times for young firn and snow, 1.5 to 3 times for old firn and 30% for ice. Avsiuk (1953, 1962) indicated that by dusting the whole area of glacier at the beginning of ablation period, the annual river runoff from mountains of Soviet Central Asia can be increased by 50-55%.

Kotlyakov and Dolgushin (1972) reported results of some experiments carried out near ports on the shore of the North Arctic Ocean, on Siberian rivers lakes of the northern part of the European territory of the USSR. A 3 to 4 times faster melting of snow cover on the ice as compared with usual melting of snowpack was observed. Best results were achieved by dusting at the rates of 300-350 g/m^2 with crushed coal and slag or 400 g/m^2 with sand and coal mixture.

Studies related to degree-day factor for ice or dusted ice are not available for the Himalayan basins. In this study, effect of natural dust on diurnal and mean daily snowmelt and ice melt factors or accelerating of melt rate has been determined. The location of the experiment site is shown in Figure 1. It is to be mentioned that, in general, access to the glaciers is very difficult because of very rugged terrain. For example, one has to make more than 25 km trekking to carry out the present investigations. Further, climate, accessibility, accommodation and commodity problems at higher altitude make such studies very tedious in nature which results in limited observations.

The literature shows that most of the studies are reported on the effect of dust on the melting of snow and no study on the effect of dust on the ice melting is found in literature.

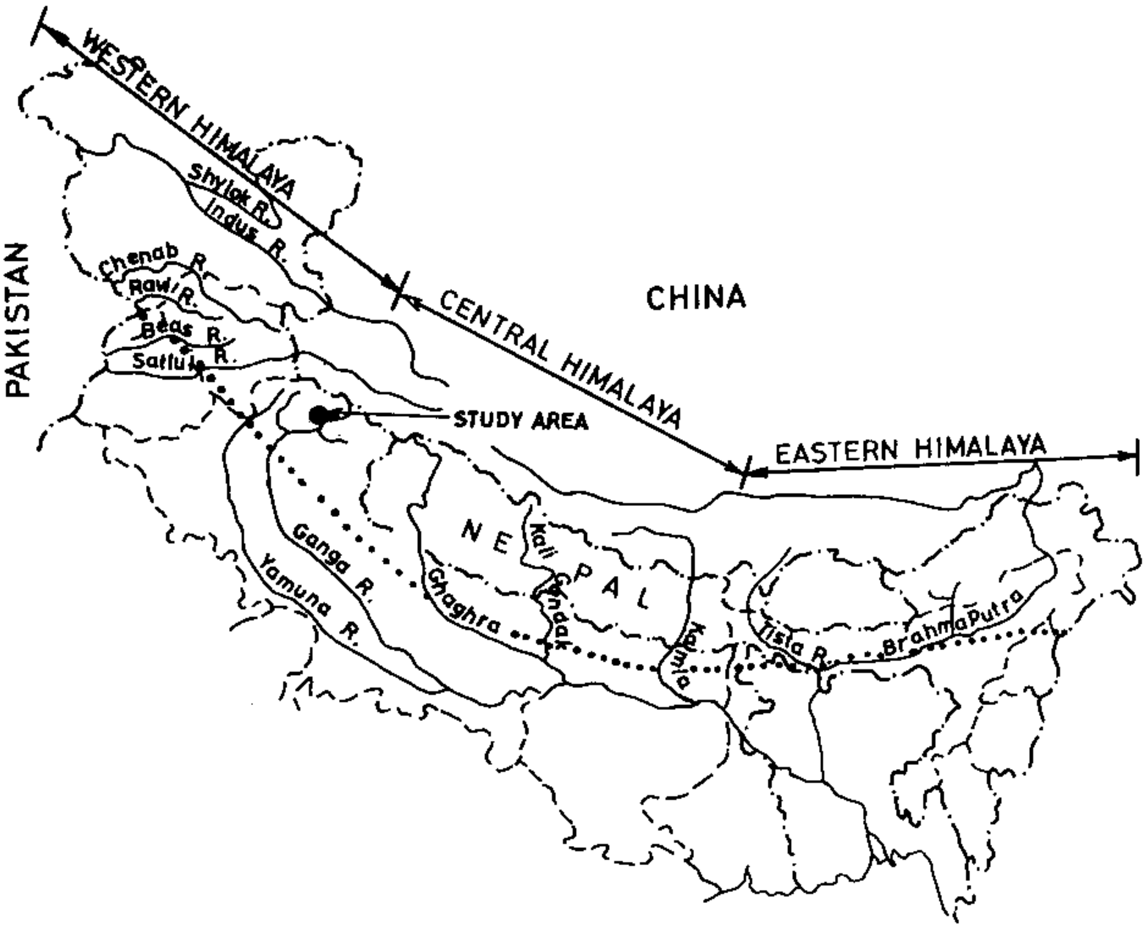

Figure 1: Location of Study Area

3.0 SETTING UP OF SNOW AND ICE BLOCK EXPERIMENTS

It is possible to compute degree-day factor at a point by measuring temperature and melt water from the snow or ice block. The number of degree-days for one day is obtained by averaging positive air temperatures. The point measurements can be used for information on how well a specific station represents the hydrological characteristics of a given basin. Singh et al. (1995) made some calculations of snow melt factor by studying the isolated snow blocks for a part of the day only. Moreover, a study of isolated snow block to determine the snow melt factor does not represent the actual melting situation of the snowpack because isolated snow block receives additional energy from all exposed sides of the block. Therefore, these values are of limited use. In the case of natural melting of a snowpack, energy is received through upper surface of the snowpack. Therefore, to obtain more reliable and accurate information on degree-day factors for snow and ice, snow and ice blocks have been monitored in the snowpack only. All the experiments have been carried out under fair weather conditions. The location of study area is shown in Figure 1. Details of clean and dusted snow and ice blocks experiments are given below.

3.1 Clean snow and ice blocks

In order to determine degree-day factors for snow and ice, snow and ice blocks, each having 30cm × 30cm × 30cm dimensions, were extracted from the glacier snowpack and ice body at an altitude of about 4000m without disturbing their natural structure. However, a minor treatment was given on the outer side of the snow block to bring it into exactly required dimensions. The density of the snow block and ice block was 0.60 and 0.90 gm/cc, respectively. The snow block was compact enough at this density and it was easy to extract a snow block of the required dimension from the snowpack. Similar to snow blocks, ice blocks were also cut from the ice body of the glacier. Because the cutting of ice is not as easy as that of snow, therefore, extraction of ice block from the ice body was difficult as compared to the snow block.

The snow block and ice block were properly wrapped in the plastic sheet from all the sides, except upper one, and again fitted in the snowpack. The location of snow block was very close to the ice block. The upper surface level of the snow and ice blocks was kept same as that of snowpack in which these study blocks were inserted. All the boundaries of blocks were intact with snowpack and plastic sheet around all sides ensured that melt runoff only from the snow/ice block under study was collected in the bucket. Moreover, there was no loss of melt water in the form of infiltration or percolation from these blocks because of underneath plastic sheet.

After setting up the experiment, only upper surface of snow and ice blocks were exposed to the radiation. The melting from these blocks occurred as under natural condition of the snow and ice. Moreover, melting from the snow and ice blocks occurred in the same environment. The observations were made for 24 hours on the dates listed in Table 3.

Table 3: Period of conducting experiments in different years

Period	Study blocks
June 5, 1995	Snow block
June 6, 1995	Snow block
May, 29, 1997	Snow blocks and ice blocks
June, 24, 1998	Snow blocks and ice blocks
June ,25 1998	Snow blocks and ice blocks
July, 22, 1998	Snow blocks and ice blocks

To get a better representation of temperature within each hour, air temperature was observed every 15 minutes interval at 2 m height above the snow surface and was used to compute the average temperature for each hour. The melt water was collected in a bucket at a frequency of one hour and measured immediately after collection to minimize the evaporation losses from the collected volume of water.

3.2 Dusted snow and ice blocks

Dusting or blackening of snow and ice surfaces by the dark material brings down its albedo. It results in higher absorption of solar radiation leading to accelerated melt rate and higher melt water yield. The accelerating rate of melt depends on the radiation absorbing property of the dusting material. However, there are several materials like charcoal powder, boiler ash, wood ash and common salt etc., but in the present study the natural dust available at 4000m altitude over the glacier surface was used as dusting material. It is the material which in fact covers the glacier surface and affects the melt rate. The dust consisted of mainly moraines and debris powder having particles coarse in size. No treatment was given to dust in terms of changing the size of the particles.

To study the effect of dusting on melting behaviour of snow and ice, and therefore on degree-day factor for snow and ice, another set of snow and ice blocks were extracted and placed in the snowpack like the normal snow block. The size and density of the snow and ice blocks used for dusting effect were similar to the normal snow and ice blocks, respectively, except the upper surface of these blocks was covered by an uniform 2 mm thick layer of the natural dust. However, various depth of this dust was found at different locations over the snowpack, but for this experiment a uniform depth of 2 mm thickness was selected simply because this depth was found at several locations. Location wise, the dust free and dusted snow blocks were adjacent so that both blocks experience the same weather conditions. The frequency and period of observations for the air temperature and melt water were exactly same for all the snow and ice blocks.

All the experiments described above were carried out for a period of 1 day. It was preferred to set up a new experiment at 0800 hours every day and study for next 24 hours. Study of the same blocks for the next day was not continued because the objective of the experiment was to study the effect of uniform dust layer on degree-day factor for snow and ice. It was noticed that if experiment was extended beyond 24 hours period, a part of the dust spread over the snow surface percolates in to the snow block with melt water leaving a non-uniform dust layer over the snow block. Moreover, due to accelerated melt rate, the dusted snow block sinks relatively faster and surface level of both blocks is changed. Under these circumstances, dusted snow block is not exposed to solar radiation like the normal snow block. In the case of ice block, much of the dust was removed from the ice surface with melt water as surface flow because of impermeability of ice.

4.0 RESULTS AND DISCUSSIONS

4.1 Diurnal variation in runoff from snow and ice blocks

Diurnal variation in runoff generated from the snow and ice blocks for clean and dusted conditions for different experiments have been demonstrated in Figure 2 through 5. Air temperature observed 2 m above the snowpack is also illustrated along with runoff. The rise and fall in the runoff observed from the study blocks is governed by the distribution of temperature above these blocks. The trend of runoff distribution observed from all clean and dusted blocks indicates that it starts rising between 0900-1000 hours and attains its maximum value usually at about 1200 -1300 hours. After that it starts reducing and reaches to zero by about 1900-2000 hours.

Runoff from the dusted blocks, whether it was snow or ice block, was observed late than the respective clean block. The exact delay period could not be ascertained from these investigations because discharge observation frequency was one hour, and delay period was also about in the same range. In fact, to determine the actual delay time on the block scale, discharge observations at higher frequency are needed. The total volume of runoff observed from ice block was higher than snow because of higher melt rate of ice under the same temperature conditions,. Moreover, results indicate that melt runoff from a clean or dusted ice block follows a sharp rise and recession as compared with clean or dusted snow block. For both snow and ice blocks, diurnal variation in the melt runoff shows that except in the beginning of melt, almost all the time runoff from the dusted blocks was higher than the respective clean blocks. As such diurnal variation of both snow and ice melt factors followed that similar pattern.

Diurnal variation in hourly melt factor is shown in Table 5. The time of maximum value of the hourly melt factor is controlled by the distribution of temperature. It is observed that maximum value of the hourly snow and ice melt factor occurred at about 1200-1300 hours for both clean and dusted blocks. During experiments conducted in different months and years, the range of maximum value of hourly snow melt factor for clean and dusted snow blocks was 0 to 0.946 and 0 to 1.13 mm°C^{-1} hr^{-1}, respectively. This range for clean and dusted ice block was 0 to 1.152 and 0 to 1.335, respectively. It is observed that at the time of experiment, air temperature was above 0 °C. The hourly observed air temperature and melt factor runoff from the snow blocks are shown in Table 4.

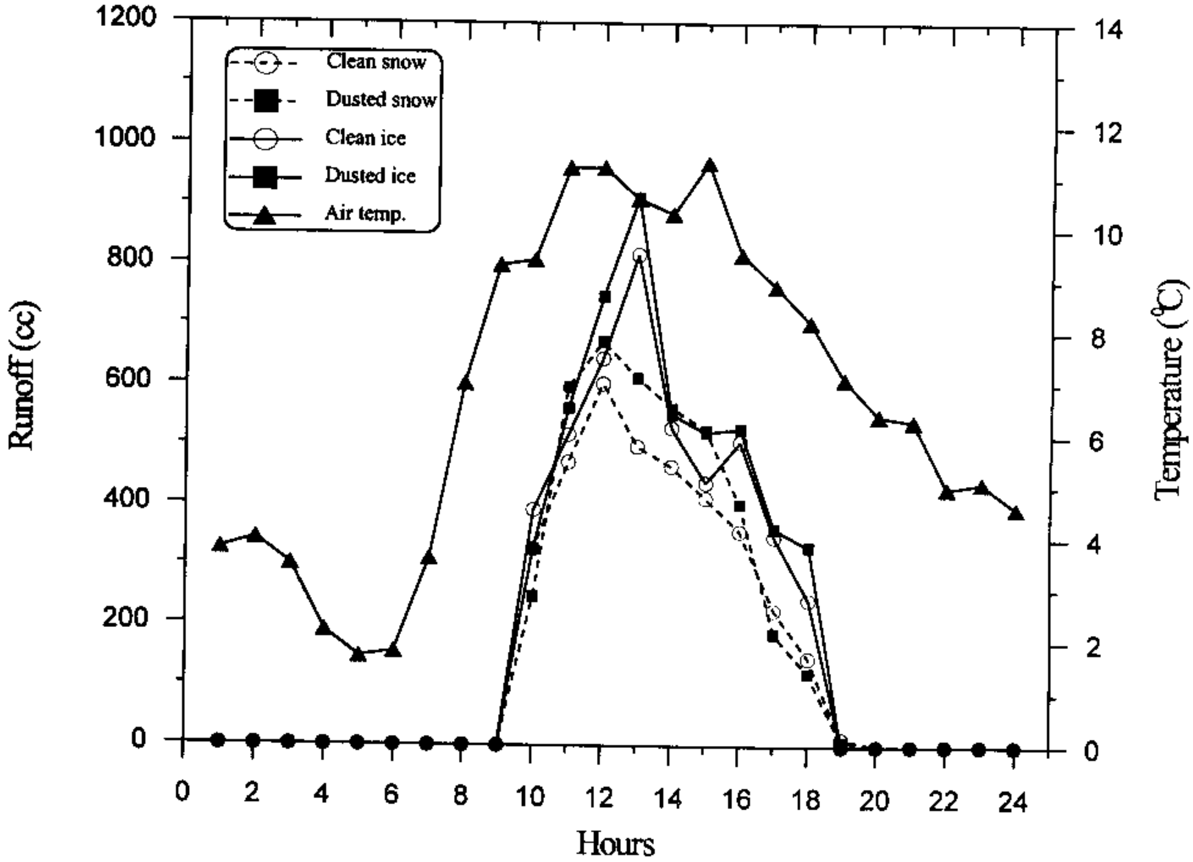

Figure 2: Melt runoff from clean and dusted snow and ice blocks along with air temperature observed on 29.5.1997.

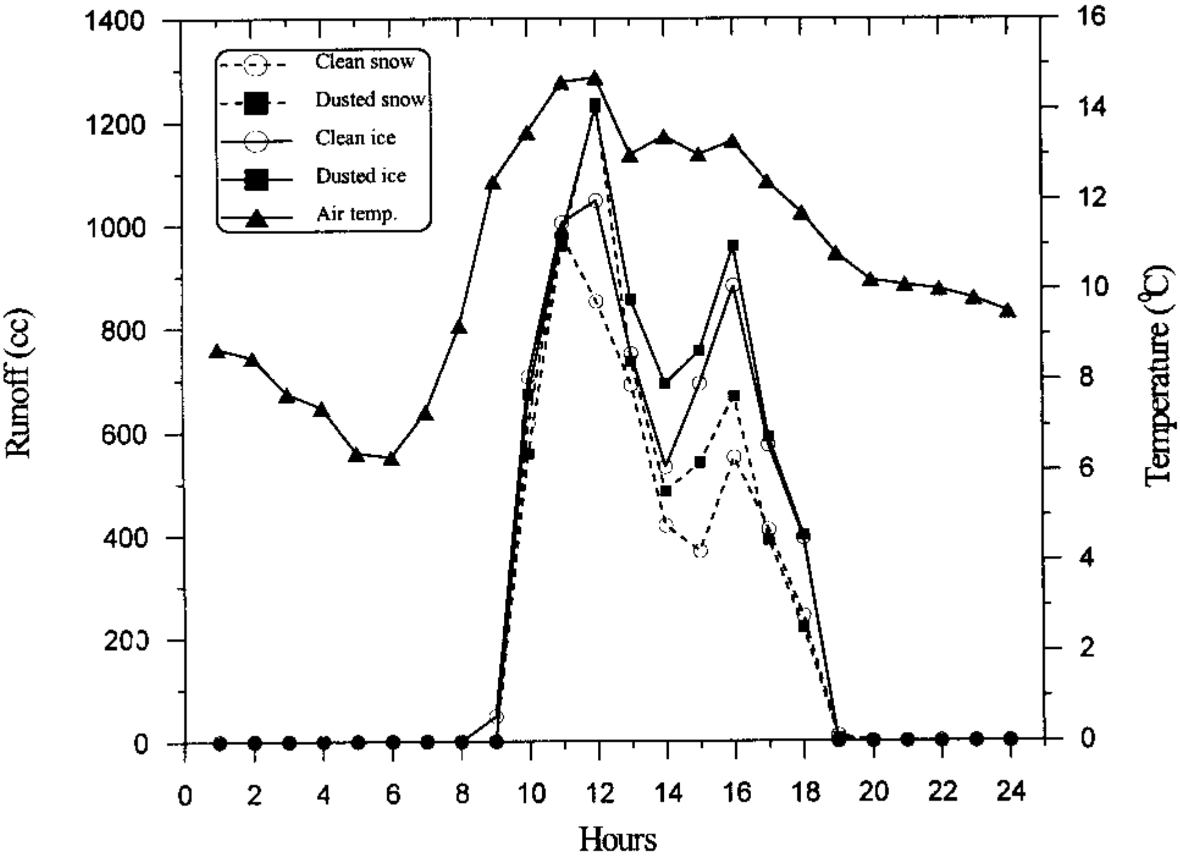

Figure 3: Melt runoff from clean and dusted snow and ice blocks along with air temperature observed on 24.6.1998.

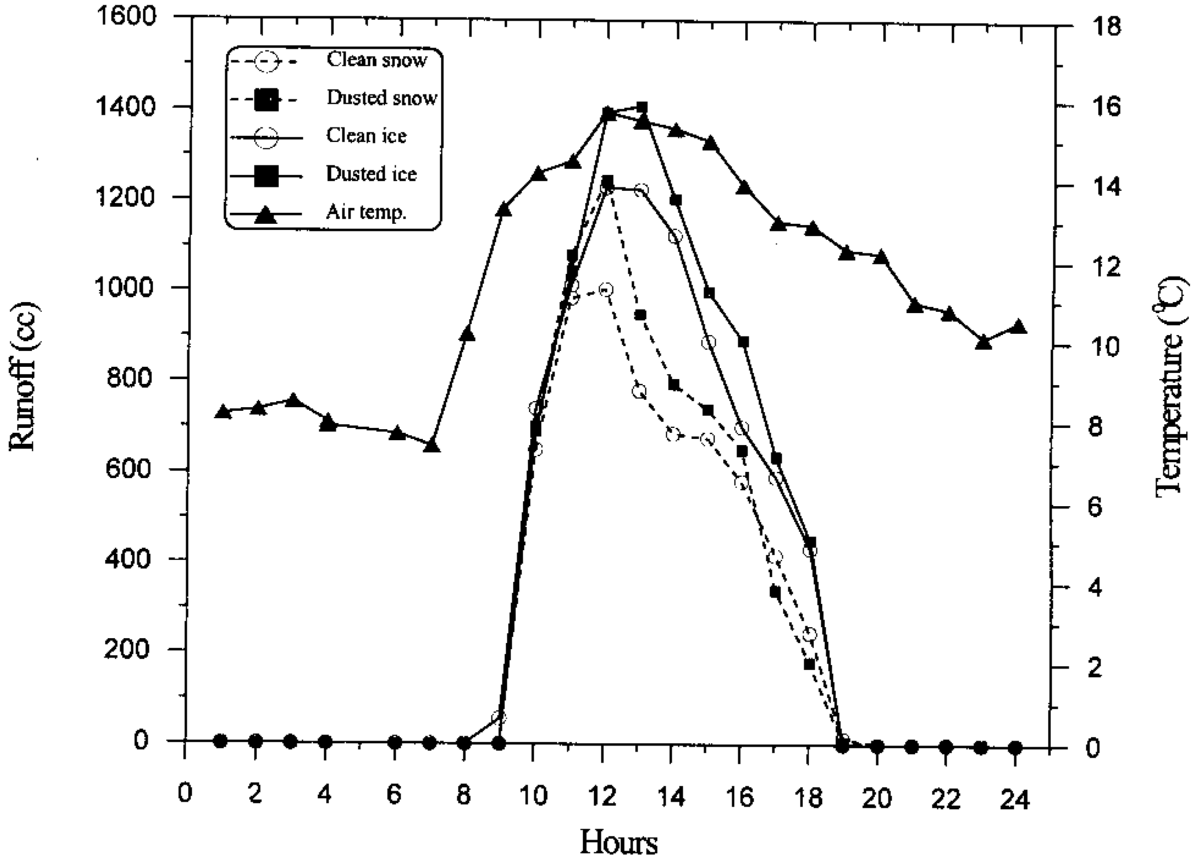

Figure 4: Melt runoff from clean and dusted snow and ice blocks along with air temperature observed on 25.6.1998.

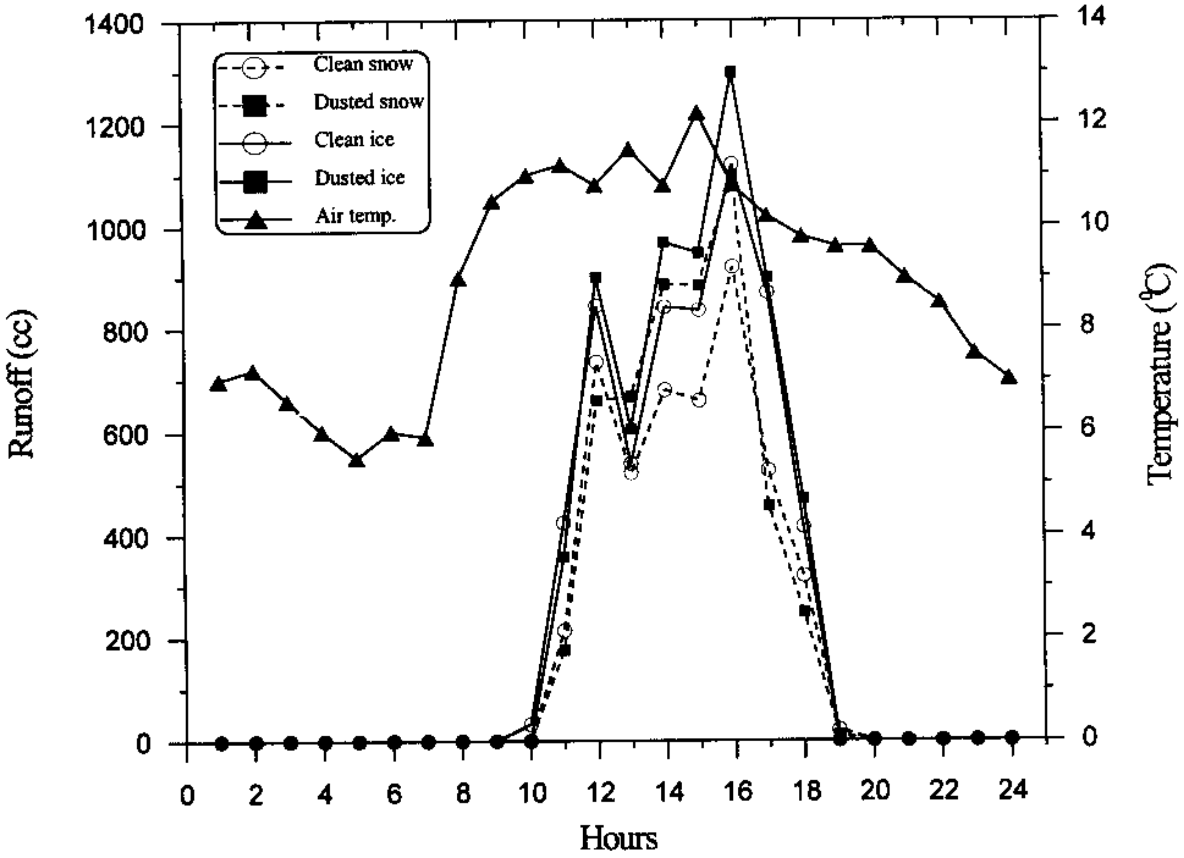

Figure 5: Melt runoff from clean and dusted snow and ice blocks along with air temperature observed on 22.7.1998.

Table 4(a): Air temperatures recorded over the snow surface and runoff observed from the clean and dusted snow blocks under same weather conditions. The dimensions of both snow blocks were 30cm × 30cm ×30cm.

Date	Hours	Air temperature at 2 m above surface (°C)	Runoff from clean snow block (cc)	Runoff from dusted snow block (cc)
5.6.1995	0000-0100	6.3	0	0
	0100-0200	7.7	0	0
	0200-0300	7.5	0	0
	0300-0400	7.0	0	0
	0400-0500	6.4	0	0
	0500-0600	6.2	0	0
	0600-0700	10.4	0	0
	0700-0800	15.5	0	0
	0800-0900	16.8	50	0
	0900-1000	19.0	390	620
	1000-1100	20.4	700	950
	1100-1200	21.2	920	1230
	1200-1300	20.6	990	1300
	1300-1400	19.8	1000	1470
	1400-1500	19.6	1030	1340
	1500-1600	18.2	870	560
	1600-1700	16.3	610	210
	1700-1800	15.0	260	60
	1800-1900	12.5	110	10
	1900-2000	11.0	40	0
	2000-2100	10.2	0	0
	2100-2200	9.2	0	0
	2200-2300	8.3	0	0
	2300-2400	7.0	0	0

Table 4(b): Air temperatures recorded over the snow surface and runoff observed from the clean and dusted snow blocks under same weather conditions. The dimensions of both snow blocks were 30cm × 30cm × 30cm.

Date	Hours	Air temperature at 2m above surface (°C)	Runoff from normal snow block (cc)	Runoff from dusted snow block (cc)
6.6.1995	0000-0100	6.7	0	0
	0100-0200	6.9	0	0
	0200-0300	7.0	0	0
	0300-0400	7.2	0	0
	0400-0500	8.3	0	0
	0500-0600	9.6	0	0
	0500-0700	14.7	0	0
	0800-0900	17.3	60	0
	0900-1000	19.2	380	620
	1000-1100	20.5	760	1020
	1100-1200	21.5	930	1300
	1200-1300	21.3	1010	1340
	1300-1400	20.5	990	1460
	1400-1500	19.5	1080	1320
	1500-1600	18.7	900	570
	1600-1700	16.9	700	290
	1700-1800	15.6	250	60
	1800-1900	13.0	100	10
	1900-2000	11.2	30	0
	2000-2100	10.3	0	0
	2100-2200	9.4	0	0
	2200-2300	9.0	0	0
	2300-2400	8.6	0	0

Table 4(c): Air temperatures recorded over the snow surface and runoff observed from the clean and dusted snow blocks under same weather conditions. The dimensions of both snow blocks were 30cm × 30cm × 30cm.

Date	Hours	Air temp. at 2m above surface (°C)	Runoff from clean snow block (cc)	Runoff from dusted snow block (cc)	Runoff from normal ice block (cc)	Runoff from dusted ice block (cc)
29.5.97	0000-0100	3.8	0	0	0	0
	0100-0200	4.0	0	0	0	0
	0200-0300	3.5	0	0	0	0
	0300-0400	2.2	0	0	0	0
	0400-0500	1.7	0	0	0	0
	0500-0600	1.8	0	0	0	0
	0600-0700	3.6	0	0	0	0
	0700-0800	7.0	0	0	0	0
	0800-0900	9.3	0	0	0	0
	0900-1000	9.4	325	245	390	325
	1000-1100	11.2	470	595	516	560
	1100-1200	11.2	600	670	642	746
	1200-1300	10.6	496	610	825	910
	1300-1400	10.3	463	560	527	550
	1400-1500	11.3	410	524	436	520
	1500-1600	9.5	355	400	504	526
	1600-1700	8.9	224	185	346	360
	1700-1800	8.2	145	120	241	330
	1800-1900	7.1	12	8	0	0
	1900-2000	6.4	0	0	0	0
	2000-2100	6.3	0	0	0	0
	2100-2200	5.0	0	0	0	0
	2200-2300	5.1	0	0	0	0
	2300-2400	4.6	0	0	0	0

Table 4(d): Air temperatures recorded over the snow surface and runoff observed from the clean and dusted snow blocks under same weather conditions. The dimensions of both snow blocks were 30cm × 30cm × 30cm.

Date	Hours	Air temp. at 2m above surface (°C)	Runoff from clean snow block (cc)	Runoff from dusted snow block (cc)	Runoff from clean ice block (cc)	Runoff from dusted ice block (cc)
24.6.98	0000-0100	8.7	0	0	0	0
	0100-0200	8.5	0	0	0	0
	0200-0300	7.7	0	0	0	0
	0300-0400	7.4	0	0	0	0
	0400-0500	6.4	0	0	0	0
	0500-0600	6.3	0	0	0	0
	0600-0700	7.3	0	0	0	0
	0700-0800	9.2	0	0	0	0
	0800-0900	12.4	0	0	48	0
	0900-1000	13.5	616	558	706	672
	1000-1100	14.6	980	960	1005	980
	1100-1200	14.7	852	1236	1048	1230
	1200-1300	13.0	690	735	750	855
	1300-1400	13.4	418	485	532	692
	1400-1500	13.0	368	540	692	756
	1500-1600	13.3	550	668	882	960
	1600-1700	12.4	410	390	574	590
	1700-1800	11.7	242	220	394	400
	1800-1900	10.8	10	6	0	0
	1900-2000	10.2	0	0	0	0
	2000-2100	10.1	0	0	0	0
	2100-2200	10.0	0	0	0	0
	2200-2300	9.8	0	0	0	0
	2300-2400	9.5	0	0	0	0

Table 4(e): Air temperatures recorded over the snow surface and runoff observed from the clean and dusted snow blocks under same weather conditions. The dimensions of both snow blocks were 30cm × 30cm × 30cm.

Date	Hours	Air temp. at 2m above surface (°C)	Runoff from clean snow block (cc)	Runoff from dusted snow block (cc)	Runoff from clean ice block (cc)	Runoff from dusted ice block (cc)
25.6.98	0000-0100	8.2	0	0	0	0
	0100-0200	8.3	0	0	0	0
	0200-0300	8.5	0	0	0	0
	0300-0400	8.0	0	0	0	0
	0400-0500	7.9	0	0	0	0
	0500-0600	7.7	0	0	0	0
	0600-0700	7.4	0	0	0	0
	0700-0800	10.2	0	0	0	0
	0800-0900	13.3	0	0	55	0
	0900-1000	14.2	650	700	741	690
	1000-1100	14.5	985	1080	1014	1045
	1100-1200	15.7	1005	1248	1230	1396
	1200-1300	15.5	780	950	1225	1410
	1300-1400	15.3	685	795	1124	1205
	1400-1500	15.0	675	740	890	1000
	1500-1600	13.9	580	650	700	892
	1600-1700	13.0	416	340	590	635
	1700-1800	12.9	245	180	431	450
	1800-1900	12.3	12	6	0	0
	1900-2000	12.2	0	0	0	0
	2000-2100	11.0	0	0	0	0
	2100-2200	10.8	0	0	0	0
	2200-2300	10.1	0	0	0	0
	2300-2400	10.5	0	0	0	0

Table 4(f): Air temperatures recorded over the snow surface and runoff observed from the clean and dusted snow blocks under same weather conditions. The dimensions of both snow blocks were 30cm × 30cm × 30cm.

Date	Hours	Air temp. at 2m above surface (°C)	Runoff from clean snow block (cc)	Runoff from dusted snow block (cc)	Runoff from clean ice block (cc)	Runoff from dusted ice block (cc)
22.7.98	0000-0100	7.0	0	0	0	0
	0100-0200	7.2	0	0	0	0
	0200-0300	6.6	0	0	0	0
	0300-0400	6.0	0	0	0	0
	0400-0500	5.5	0	0	0	0
	0500-0600	6.0	0	0	0	0
	0600-0700	5.9	0	0	0	0
	0700-0800	9.0	0	0	0	0
	0800-0900	10.5	0	0	5	0
	0900-1000	11.0	0	0	32	0
	1000-1100	11.2	214	176	424	358
	1100-1200	10.8	734	660	844	900
	1200-1300	11.5	520	668	538	605
	1300-1400	10.8	680	886	842	968
	1400-1500	12.2	660	884	836	948
	1500-1600	10.8	920	1098	1120	1298
	1600-1700	10.2	524	456	870	900
	1700-1800	9.8	320	248	415	470
	1800-1900	9.6	20	10	0	0
	1900-2000	9.6	0	0	0	0
	2000-2100	9.0	0	0	0	0
	2100-2200	8.5	0	0	0	0
	2200-2300	7.5	0	0	0	0
	2300-2400	7.0	0	0	0	0

Table 5(a) : Hourly melt factor and air temperatures recorded over the snow surface and runoff observed from the clean and dusted snow blocks under same weather conditions. The dimensions of both snow blocks were 30cm × 30cm × 30cm.

Date	Hours	Air temperature at 2m above snow surface (°C)	Hourly melt factor for clean snow block (mm°C^{-1} hr^{-1})	Hourly melt factor for dusted snow (mm°C^{-1} hr^{-1})
5.6.1995	0000-0100	6.3	0	0
	0100-0200	7.7	0	0
	0200-0300	7.5	0	0
	0300-0400	7.0	0	0
	0400-0500	6.4	0	0
	0500-0600	6.2	0	0
	0600-0700	10.4	0	0
	0700-0800	15.5	0	0
	0800-0900	16.8	.033	0
	0900-1000	19.0	.228	.362
	1000-1100	20.4	.381	.517
	1100-1200	21.2	.482	.645
	1200-1300	20.6	.534	.701
	1300-1400	19.8	.561	.825
	1400-1500	19.6	.584	.760
	1500-1600	18.2	.531	.342
	1600-1700	16.3	.416	.143
	1700-1800	15.0	.192	.044
	1800-1900	12.5	.098	.009
	1900-2000	11.0	.040	0
	2000-2100	10 2	0	0
	2100-2200	9.2	0	0
	2200-2300	8.3	0	0
	2300-2400	7.0	0	0

Table 5(b): Hourly melt factor and air temperatures recorded over the snow surface and runoff observed from the clean and dusted snow blocks under same weather conditions. The dimensions of both snow blocks were 30cm × 30cm × 30 cm.

Date	Hours	Air temperature at 2 m above the snow surface (°C)	Hourly melt factor for clean snow block (mm°C^{-1} hr^{-1})	Hourly melt factor for dusted snow block (mm°C^{-1} hr^{-1})
6.6.1995	0000-0100	6.7	0	0
	0100-0200	6.9	0	0
	0200-0300	7.0	0	0
	0300-0400	7.2	0	0
	0400-0500	8.3	0	0
	0500-0600	9.6	0	0
	0500-0700	14.7	0	0
	0800-0900	17.3	.038	0
	0900-1000	19.2	.220	.359
	1000-1100	20.5	.412	.553
	1100-1200	21.5	.487	.672
	1200-1300	21.3	.527	.699
	1300-1400	20.5	.536	.791
	1400-1500	19.5	.615	.752
	1500-1600	18.7	.535	.339
	1600-1700	16.9	.460	.190
	1700-1800	15.6	.178	.043
	1800-1900	13.0	.085	.008
	1900-2000	11.2	.030	0
	2000-2100	10.3	0	0
	2100-2200	9.4	0	0
	2200-2300	9.0	0	0
	2300-2400	8.6	0	0

Table 5(c): Hourly melt factor and air temperatures recorded over the snow surface and runoff observed from the clean and dusted snow blocks under same weather conditions. The dimensions of both snow blocks were 30cm × 30cm × 30cm.

Date	Hours	Air temp. at 2m above surface (°C)	Hourly melt factor for clean snow (mm°C^{-1} hr^{-1})	Hourly melt factor for dusted snow (mm°C^{-1} hr^{-1})	Hourly melt factor for clean ice (mm°C^{-1} hr^{-1})	Hourly melt factor for dusted ice (mm°C^{-1} hr^{-1})
29.5.97	0000-0100	3.8	0	0	0	0
	0100-0200	4.0	0	0	0	0
	0200-0300	3.5	0	0	0	0
	0300-0400	2.2	0	0	0	0
	0400-0500	1.7	0	0	0	0
	0500-0600	1.8	0	0	0	0
	0600-0700	3.6	0	0	0	0
	0700-0800	7.0	0	0	0	0
	0800-0900	9.3	0	0	0	0
	0900-1000	9.4	.384	.290	.461	.384
	1000-1100	11.2	.466	.590	.512	.556
	1100-1200	11.2	.595	.665	.637	.74
	1200-1300	10.6	.520	.639	.854	.954
	1300-1400	10.3	.499	.604	.568	.593
	1400-1500	11.3	.403	.515	.429	.511
	1500-1600	9.5	.415	.468	.589	.615
	1600-1700	8.9	.280	.231	.462	.449
	1700-1800	8.2	.196	.163	.327	.447
	1800-1900	7.1	.019	.013	0	0
	1900-2000	6.4	0	0	0	0
	2000-2100	6.3	0	0	0	0
	2100-2200	5.0	0	0	0	0
	2200-2300	5.1	0	0	0	0
	2300-2400	4.6	0	0	0	0

Table 5(d): Hourly melt factor and air temperatures recorded over the snow surface and runoff observed from the normal and dusted snow blocks under same weather conditions. The dimensions of both snow blocks were 30cm × 30cm × 30cm.

Date	Hours	Air temp. at 2m above surface (°C)	Hourly melt factor for clean snow block (mm°C^{-1} hr^{-1})	Hourly melt factor for dusted snow block (mm°C^{-1} hr^{-1})	Hourly melt factor for clean ice block (mm°C^{-1} hr^{-1})	Hourly melt factor for dusted ice block (mm°C^{-1} hr^{-1})
24.6.98	0000-0100	8.7	0	0	0	0
	0100-0200	8.5	0	0	0	0
	0200-0300	7.7	0	0	0	0
	0300-0400	7.4	0	0	0	0
	0400-0500	6.4	0	0	0	0
	0500-0600	6.3	0	0	0	0
	0600-0700	7.3	0	0	0	0
	0700-0800	9.2	0	0	0	0
	0800-0900	12.4	0	0	.043	0
	0900-1000	13.5	.507	.459	.581	.553
	1000-1100	14.6	.746	.731	.765	.746
	1100-1200	14.7	.644	.934	.792	.930
	1200-1300	13.0	.590	.628	.641	.731
	1300-1400	13.4	.347	.402	.441	.574
	1400-1500	13.0	.314	.462	.591	.646
	1500-1600	13.3	.460	.558	.737	.802
	1600-1700	12.4	.367	.349	.514	.529
	1700-1800	11.7	.230	.209	.374	.380
	1800-1900	10.8	.010	.006	0	0
	1900-2000	10.2	0	0	0	0
	2000-2100	10.1	0	0	0	0
	2100-2200	10.0	0	0	0	0
	2200-2300	9.8	0	0	0	0
	2300-2400	9.5	0	0	0	0

Table 5(e): Hourly melt factor and air temperatures recorded over the snow surface and runoff observed from the normal and dusted snow blocks under same weather conditions. The dimensions of both snow blocks were 30cm × 30cm × 30cm.

Date	Hours	Air temp. at 2m above surface (°C)	Hourly melt factor for clean snow block (mm°C^{-1} hr^{-1})	Hourly melt factor for dusted snow block (mm°C^{-1} hr^{-1})	Hourly melt factor for clean ice block (mm°C^{-1} hr^{-1})	Hourly melt factor for dusted ice block (mm°C^{-1} hr^{-1})
25.6.98	0000-0100	8.2	0	0	0	0
	0100-0200	8.3	0	0	0	0
	0200-0300	8.5	0	0	0	0
	0300-0400	8.0	0	0	0	0
	0400-0500	7.9	0	0	0	0
	0500-0600	7.7	0	0	0	0
	0600-0700	7.4	0	0	0	0
	0700-0800	10.2	0	0	0	0
	0800-0900	13.3	0	0	.046	0
	0900-1000	14.2	.509	.548	.57	.54
	1000-1100	14.5	.755	.828	.777	.801
	1100-1200	15.7	.711	.883	.87	.988
	1200-1300	15.5	.559	.681	.878	1.010
	1300-1400	15.3	497	.577	.816	.875
	1400-1500	15.0	.500	.548	.659	.741
	1500-1600	13.9	.464	.52	.559	.713
	1600-1700	13.0	.356	.291	.504	.543
	1700-1800	12.9	.211	.155	371	.388
	1800-1900	12.3	.011	.005	0	0
	1900-2000	12.2	0	0	0	0
	2000-2100	11.0	0	0	0	0
	2100-2200	10.8	0	0	0	0
	2200-2300	10.1	0	0	0	0
	2300-2400	10.5	0	0	0	0

Table 5(f): Hourly melt factor and air temperatures recorded over the snow surface and runoff observed from the normal and dusted snow blocks under same weather conditions. The dimensions of both snow blocks were 30cm × 30cm × 30cm.

Date	Hours	Air temp. at 2m above surface (°C)	Hourly melt factor for clean snow block ($mm°C^{-1} hr^{-1}$)	Hourly melt factor for dusted snow block ($mm°C^{-1} hr^{-1}$)	Hourly melt factor for clean ice block ($mm°C^{-1} hr^{-1}$)	Hourly melt factor for clean ice block ($mm°C^{-1} hr^{-1}$)
22.7.98	0000-0100	7.0	0	0	0	0
	0100-0200	7.2	0	0	0	0
	0200-0300	6.6	0	0	0	0
	0300-0400	6.0	0	0	0	0
	0400-0500	5.5	0	0	0	0
	0500-0600	6.0	0	0	0	0
	0600-0700	5.9	0	0	0	0
	0700-0800	9.0	0	0	0	0
	0800-0900	10.5	0	0	0	0
	0900-1000	11.0	0	0	.032	0
	1000-1100	11.2	.212	.175	.420	.355
	1100-1200	10.8	.755	.679	.868	.926
	1200-1300	11.5	.502	.645	.52	.584
	1300-1400	10.8	.7	.911	.866	.996
	1400-1500	12.2	.601	.805	.761	.863
	1500-1600	10.8	.946	1.13	1.152	1.335
	1600-1700	10.2	.571	.497	.948	.98
	1700-1800	9.8	.363	.281	.471	.533
	1800-1900	9.6	.023	.012	0	0
	1900-2000	9.6	0	0	0	0
	2000-2100	9.0	0	0	0	0
	2100-2200	8.5	0	0	0	0
	2200-2300	7.5	0	0	0	0
	2300-2400	7.0	0	0	0	0

The diurnal variation in the snow and ice melt factor for both clean and dusted snow blocks can be explained on the basis of change of albedo or energy absorbed by the melting surface. Albedo of snow varies with angle of the incidence of radiation and also depends on the characteristics of energy receiving surface. A higher value of albedo is associated with larger angle of incidence (U. S. Army Corps of Engineers, 1956). In the case of snow, however, this variation may also be partially the result of changes in the structure of snow itself during the day. For example, when melt rate is at a maximum, the higher concentration of the liquid water in the top layers of the snowpack decreases the albedo. In the case of dust free snow block, whatever quantity of heat is absorbed by the snow surface, it is utilized in the melting of snow block because snow surface is directly exposed to the radiation. But, when a snow surface is covered by dust layer, the heat is transferred to the snow surface through dust medium, which affects melting rate of snow. A dust layer over the snow block reduces the albedo markedly causing more absorption of solar radiation. It appears that in the first part of the day, lower sun angle and dusting of snow surface both play a significant role in reduction of albedo. It results in higher quantity of absorption of solar radiation by the dusted surface which is transferred to the snow block and an accelerated melting of snow is observed. As the sun angle increases, albedo also increases causing in a decrease in the absorbed radiation. However, the radiation absorbed by the dusted surface will be always higher than the normal snow block, but it is possible that when as such quantity of energy absorbed by the dusted snow surface is very low, transfer of absorbed energy through this medium is not as effective as radiation absorbed by the directly exposed snow surface. Under such circumstances, a lower melting rate of dusted snow block is expected which occurs in the later part of the day.

4.2 Daily snow and ice melt factors

The daily values of degree-day factor for snow and ice for clean and dusted snow and ice blocks have been calculated and are given in Table 6. In order to obtain these values, hourly (0000-2400 hours) air temperature and runoff data are used to work out average temperature and total runoff during the said period. It can be seen that in all the cases, daily degree-day factor for a dusted snow block is higher than the clean snow block. For different years, degree-day factor for clean snow varied from 5.39 to 5.99 mm°C^{-1} d^{-1}, whereas for dusted snow it varied from 6.09 to 6.66 mm°C^{-1} d^{-1}. Based on these observations, an average value of degree-day factor for clean and dusted snow block is computed to be 5.75 and 6.41 mm°C^{-1} d^{-1}, respectively. It shows an increase of about 11.51% in the daily SMF due to normal dusting of 2mm uniform thickness. However magnitude of the acceleration in melting depends on the type and depth of the dusting material.

Likewise the degree-day factor for dusted snow, the value of degree-day factor for dusted ice is also higher as compared to the clean ice block. The degree-day factor for clean ice was determined in the range from 6.96 to 7.71 mm°C^{-1} d^{-1}, whereas for dusted ice it ranged from 7.49 to 8.41 mm°C^{-1} d^{-1}. The average value of degree-day factor for clean ice is 7.33 mm°C^{-1} d^{-1}, whereas for dusted ice it was 7.97 mm°C^{-1} d^{-1}. On average degree-day factor for ice was about 8.70% higher than the clean ice.

A comparison of degree-day factors for clean snow and clean ice indicates that degree-day factor for ice is higher than the degree-day factor for snow. Different experiments indicated that on average degree-day factor for ice was about 27.18% higher than that of snow. Such increase in degree-day factor for ice is possible because of lower albedo of ice, and absorption of higher energy which is used to melt the ice. Results indicate that presence of dust on the ice increased the degree-day factor by about 8.90%, whereas for snow the degree-day factor was increased by about 11.51%. Thus, effect of dust on degree-day factor for snow is more than the degree-day factor for ice. The variation in degree-day factor due to dust for a particular surface depends on the degree of variation in the absorbing capacity of surface due to dust. For snow, a higher increase in degree-day factor is possible due to relatively large variation in albedo of snow because of availability of dust on its surface. In the case of ice, the variation in albedo will be less because albedo of ice is already lower. Secondly, the impermeable nature of the ice surface also helps in reducing the influence of dust on the degree-day factor of ice. In the case of ice surface which is impermeable, a part of the dust put on the ice surface is removed away from the surface along with the melt water because melt water travels as overland flow over the ice surface. Whereas in the case of snow, dust particles persist for longer time on the snow surface because of porous character of snow. The dust particles are sunk into the snow surface

Table 6: Degree-day factors for clean and dusted snow and ice for different years using daily average temperature as a mean of hourly (0000-2400 hours) temperature data. Increase in degree-day factors for snow and ice due to dusting of snow and ice is also indicated.

Date	Degree-day factor for snow, D_{sf} (mmEC^{-1}d^{-1})			Degree-day factor for ice, D_{if} (mmEC^{-1}d^{-1})		
	Clean snow	Dusted snow	Increase due to dusting (%)	Clean ice	Dusted ice	Increase due to dusting (%)
5.6.1995	5.95	6.61	11.11	-	-	-
6.6.1995	5.99	6.66	11.26	-	-	-
29.5.1997	5.76	6.44	10.3	7.27	7.94	9.21
24.6.1998	5.39	6.09	13.0	6.96	7.49	7.61
25.6.1998	5.82	6.45	12.1	7.71	8.41	9.09
22.7.1998	5.74	6.36	12.3	7.40	8.06	8.90
Average	5.75	6.41	11.51	7.33	7.97	8.70

and more rough surface features are produced. These are known as the radiation brush and decreases the albedo of surface, which in turn increase the melt from snow.

Daily maximum and minimum temperatures are the most readily available data for the high altitude basins. Therefore, an attempt has been made to compute degree-day factors for both clean and dusted blocks using average temperature of the day as a mean of the daily maximum and minimum temperatures. These values were compared with degree-day factors derived from the average temperature of a day computed on the mean of the 24 hourly values of temperature data. Results are shown in Table 7. It is observed that variation in degree-day factors was less than 2% when these factors were calculated taking average temperature of the day as mean of the daily maximum and minimum temperatures. Thus, on the basis of this marginal change in degree-day factor for snow and ice, it can be concluded that average temperature of a day as a mean of daily maximum and minimum temperatures, can be used in the snow melt and ice runoff calculations when hourly data are not available. This type of situation is very common in the Himalayan basins.

Table 7: Computed mean daily snow melt factor and ice melt factor for clean and dusted snow and ice blocks for different years. Daily average temperature used in the derivation of these values is used as a mean of daily maximum and minimum temperatures.

Date	Clean snow block (mm°C^{-1} d^{-1})	Dusted snow block (mm°C^{-1} d^{-1})	Clean ice block (mm°C^{-1} d^{-1})	Dusted ice block (mm°C^{-1} d^{-1})
5.6.1995	5.47	6.07	-	-
6.6.1995	5.52	6.14	-	-
29.5.1997	5.98	6.69	7.55	8.25
24.6.1998	5.43	6.14	7.02	7.55
25.6.1998	5.80	6.43	7.69	8.39
22.7.1998	5.76	6.38	7.43	8.09
Average	5.66	6.30	7.42	8.07

The mean degree-day factor value obtained for clean and dusted snow and ice blocks were compared with the earlier reported results. Yoshida (1962) has reported degree-day factor for snow in the range of 4.0-8.0 mm°C^{-1} d^{-1} for the Tadami river basin in Japan. Anderson (1973) made a detailed study on the seasonal variation in degree-day factor for snow and found it in the range of 1.32-3.66 mm°C^{-1} d^{-1}. A comparison of degree-day factor for clean snow block with these reported values of degree-day factor suggest that our values lie in the range suggested by Yoshida (1962), but these are on the higher side of the results reported by Anderson (1973).

5.0 CONCLUSIONS

Degree-day factors for snow and ice are determined by monitoring a known surface area of snow and ice blocks within the snowpack at an altitude of about 4000 m over a glacier in the Garhwal Himalayan region. The experiments have been conducted for 3 different years, namely, 1995, 1996 and 1997. Effect of 2 mm thick layer of natural debris and dust available at that altitude is studied on snow and ice degree-day factors. The degree-day factor for the clean snow and dusted snow blocks is computed to be 5.75 and 6.41 mm°C^{-1} d^{-1}, respectively, whereas degree-day factor for the clean ice and dusted ice blocks is observed to be 7.33 and 7.97 mm°C^{-1} d^{-1}, respectively. It is found that degree-day factor for clean ice is 1.25 times greater than that for clean snow. The presence of dust on the ice increased the degree-day factor by about 8.90%, whereas for snow the degree-day factor was increased by about 11.51%. Thus, effect of dust on degree-day factor for snow is more prominent than the degree-day factor for ice.

Diurnal variation in the melting behaviour of snow and ice suggest that, though, melting is accelerated by the dust layer, but no change as such is found in the time of melting, except that runoff from the dusted snow block is delayed in the beginning as compared to the clean snow block. It is possible because in the case of clean snow, heat is directly absorbed by the snow surface and used for melting of snow, whereas in the case of dusted surface heat is first absorbed by the dust and then transmitted to the snow surface. Due to this factor, runoff from the dusted surface is observed after the clean snow. However, in the case of ice, such delaying effect is reduced because melt water occurring at the surface is soon reflected as the runoff. As such the delay of runoff from the snow or block depends on the type of material and depth of material used as dust on the surface. In the present study the observation frequency of runoff was one hour, as such, effect of 2 mm thick dust on the delay of runoff from the snow or ice block could not be studied very accurately. A higher frequency of runoff observations is needed to show the runoff delaying from the snow block due to dust.

A sharp rise and fall has been observed in the hourly melt runoff from the ice blocks and therefore, in hourly melt factor of ice as compared with the snow blocks. The average maximum hourly melt factor for clean and dusted snow block are computed to be 0.706 and 0.871 mm°C^{-1}

hr^{-1}, respectively, which occurred at about 1400 hours for both blocks. The minimum hourly snow melt factor was zero for both blocks. For the ice, average maximum hourly degree-day factor for clean and dusted ice is found to be 0.919 and 1.057 mm°C^{-1} hr^{-1}, respectively.

No significant change in degree-day factors for snow and ice, with dust or without dust, was found when average temperature of the day was used as a mean of daily maximum and minimum temperatures, instead of average of 24 hours values. It confirms that average temperature of the day computed as mean of maximum and minimum temperatures is simple and good approach for using in snow melt and glacier melt runoff calculations when hourly data are not available. It is suggested that such studies should be extended to study seasonal variation in degree-day factors under different conditions in the Himalayan region.

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