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MELT WATER STORAGE CHARACTERISTICS OF THE DOKRIANI GLACIER

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Abstract

Basic characteristics of the glacier melt runoff including melting conditions in the accumulation and ablation areas of the glaciers are described. A detailed review of the storage and drainage delaying characteristics of the glacier is presented. In order to study the storage and delaying behaviour of the Dokriani glacier, continuous streamflow measurements were made near the snout of this glacier. Selected fair weather hydrographs were analysed. It was observed that in about mid July maximum glacier melt runoff near the snout was recorded between 1800 and 1900 hours whereas minimum flow was obtained between 0700 and 0800 hours. The mean travel time of melt water from ablation area was determined to be about 5-6 hours. The time-lag for the melt water from the accumulation area would be several times higher than this time-lag. Baseflow varies very slowly in comparison to the diurnal flow from the glacier. The value of ratio of maximum and minimum streamflow from the glacier varied between 1.40 and 1.50 indicating considerable runoff during the night time also. Impact of changes in accumulation and ablation area on the hydrological response of the glacier is also discussed.

1.0 INTRODUCTION

Increase in population and industrialization all over the world has enhanced the demand of water significantly. Consequently, to meet this increase in demand continuous development of new sources of water for irrigation, hydropower, domestic and industrial supply is needed. Runoff from the glacier is considered reliable and important for these purposes. The water yield from the glacierized regions is high because of high precipitation in the high altitude regions where glaciers exist. Glacier melt contribution is maximum during the summer period when the demand for water is at its maximum. Further, because streamflow from the glaciers originate from high altitude regions, therefore, availability of dependable flows and suitable head provide excellent conditions for hydropower generation. Such advantages has resulted in extensive engineering development that use glacier melt runoff in Central Asia, The Alps, Scandinavia, and the North American Cordillera. However, to develop this water resources fully a detailed understanding of melt rate, routing of melt water or storm precipitation through glaciers, glacier outburst floods is essential.

Keeping in view the glaciers as important source of water, the International Hydrological Decade (1965-74) included major programmes related to glacier Hydrology: worldwide inventory of perennial and seasonal snow and ice masses, fluctuations of glaciers, and combined heat, ice and water balances at selected glacier basins. Valuable information was gathered under these programmes which has broadened the understanding and knowledge of the subject. Results of such studies can be used for forecasting of glacier generated streamflow for hydro-electric, or irrigation purposes, prediction and avoidance of catastrophic events due to glacier-dammed lake outbursts.

2.0 MELTING ENVIRONMENT OF THE GLACIERS

Runoff from the mountainous areas consisting of melt from snow and glaciers is generated due to interaction of precipitation and prevailing thermal environment of the basins. Melting of snow and ice is controlled by available energy. The spatial and temporal variability of the energy supply controls the melt rate which in turn influences the hydrological response of the high altitude basins. Once sufficient precipitation received as snow is stored in the winter, patterns of energy available in the subsequent spring/summer season influence its quantity, quality and timings. Changes in thermal conditions dictate the hydrological response of the basin. For example, winters with lower air temperature provide colder snowpacks which requires more heat to arrive at 0°C. It results in delay of melt runoff production in the spring season.

The timing and magnitude of the melt water generated from the mountain glaciers are found different than those from snowpack on land. Sometimes, like in the early melt season, the melt rate of the snow over the glacier and on the land may be about equal, but storage characteristics of glacier delay the release of melt water from the glacier. As the melt season progresses the seasonal snowpack over the land disappears but remains on the glaciers. Conducive melting conditions eventually further depletes the snow over the glacier and glacier ice is exposed. Once the glacier ice is exposed, the melt rate increases due to lower albedo of ice as compared with snow. In the case of glaciers virtually unlimited ice volume exists for melting during the ablation period, but the amount of melt water depends on the heat balance. Temperature is considered a good index for estimating snow and ice melt because temperature depends on radiation balance.

Major contribution of the melt water is produced from the surface melting. Melting conditions of a glacier surface are to a large extent controlled by the magnitude of winter snowfall. In case there was heavy snowfall in the preceding winter, the melting in subsequent ablation season is reduced because of availability of high albedo snow over the glacier surface for longer duration. The ablation rate of the glacier surface having dirt deposition is generally uneven. The dirt affects the albedo of surface influencing the absorption of insolation. Some water is produced at the ice/rock interface due to friction and geothermal heat, but the amount of this water as compared with surface melt is very little. The sum of condensation and evaporation is near zero for a snow or ice cover (LaChapelle, 1959; Hoinkes, 1964; Wendler and Ishikawa, 1972), however, on a bare ground the evaporation exceeds condensation.

A substantial contribution of runoff from snow and glaciers is concentrated in spring and summer months. In general the maximum melt rate of a glacier does not coincide with the maximum solar radiation. For example, maximum solar radiation is observed in the month of June, but maximum melt takes place in July and August. The main reason for this difference is average albedo of the glacier surface. In the month of June when maximum solar radiation occurs, the albedo is higher due to extensive coverage of glacier surface by seasonal snow. In the months of July and August, the albedo of the glacier surface is significantly reduced because of maximum exposure of ice surface by this time. Therefore, inspite of lower radiation in July/August than June, higher melt runoff is observed in July and August.

3.0 STREAMFLOW COMPENSATING BEHAVIOUR

The streamflow compensating behaviour of the glaciers is considered an important and peculiar characteristic. Usually production of melt water from the glaciers compensate the streamflow in the dry or wet, or hot or cold years. In other words, during dry weather conditions, glacier melt runoff is increased and during wet conditions it is reduced. This process can be easily understood for the mountainous catchments where upper part of the basin contributes in the form of melt runoff from snow and glaciers and lower part contribute in the form of runoff from rain. Under the conditions when rain occurs in the lower part of the basin, normally snow is experienced in the glacierized part of the basin. Occurrence of snow over the glaciers reduces their melt rate resulting in drastic reduction in melt runoff generated from the upper part of the basin. The basic reason for reduced melt rate under newly fallen snow scenarios is the reduction in solar energy due to higher albedo of newly fallen snow. Therefore, variations in the contribution of glacier melt runoff follow the reverse trend of rainfall runoff contribution.

The compensating characteristics of a glacier fed river reduce the variability in the streamflow and play an important role in the water resources management. An analysis dealing with an examination of CV during the main ablation period suggests that the compensation effect seems to be most effective for the basins containing the glaciated area between 30-60%(CV < 0.20) (Fig. 1). A monthly distribution of CV data set computed from a runoff data set of 20 years (1964/65-1984/85) for the Aletschgletscher basin has been presented in Table 1. It can be seen that CV for this glacier varies from 0.18 (in August) to 0.58 (in April). It is understood that higher variation in the beginning of melt season may be because of large variation in melt rate intensity from year to year.

Table 1: Monthly coefficients of runoff variation (CV) for the Aletschgletscher basin over the period 1964/65 - 1984/85 (Massa/Blatten, drianage area 195 km^2, 67% glacier area)

Months	10	11	12	1	2	3	4	5	6	7	8	9	10-9
CV(%)	37	28	18	30	25	31	58	35	24	20	18	31	11

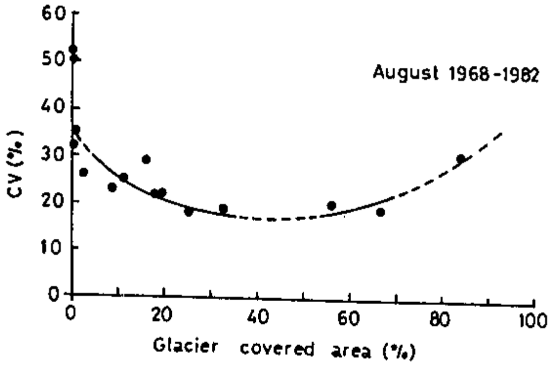

Fig. 1 : Coefficients of variation (CV) of runoff in August in relation to the percentage of glacier area for alpine river basins, fourteen of which are in the Swiss Alps (0-67% glacierized, period 1968-82) and one in the Austrian Alps (84% glacierized, period 1974-83). The compensation effect seems to be most effective at a percentage glacier area of between 30% and 60% where CV <0.2. The river basins without glaciers have a CV which is similar to that of precipitation in the area (i.e. 0.3-0.5). The basins with a high percentage glacier area also show considerable variation in runoff

4.0 FLOW CHARACTERISTICS OF A GLACIERISED BASIN

The contribution from the glaciers starts from the time at which snow is cleared from the glacier tongue. Hydrological response of a basin is governed broadly by the climate and topography. Broadly the amount of runoff produced from a glacierized basin is governed by the amount of liquid precipitation falling in the basin, the amount of ice melt from the ablation area and the amount of snowmelt occurring in the accumulation area of glacier. Flow characteristics of a glacierized basin are thus different from those of only rainfed basin. The following characteristics can be easily distinguished from the runoff from the glacierized basin:

(a) glacier ice melt provides continuous water supply throughout the summer with significant contribution in the months of July and August.

b) a major time-lag between occurrence of melting over the glacier surface and its appearance as discharge in the stream in the early summer.

c) difference between maximum and minimum discharge increases in the summer

4.1 Diurnal variation

The shape of the hydrograph exhibits the integrated effect of diurnal changes in ablation rate and hydrological response of various parts of the basin. The discharge from the glacierized basin consists of a diurnal rhythm superimposed upon a baseflow. The diurnal rhythm is considered a distinguished feature of glacier fed streams. It is primarily controlled by diurnal fluctuations in the energy available for melting of snow and ice and fast response of the ablation area of the glacier. Pronounced diurnal variations provide a hydrograph resembling saw-toothed daily peaks superimposed on a baseflow.

Examination of streamflow from the glacierized basin illustrates a considerable flow in the form of baseflow during summer period. This baseflow is controlled by storage characteristics of the glacier and determined by delayed response of the basin. Continuous drainage of water from various parts/locations governs the volume of baseflow. It indicates that only a portion of the melt water produced each day reaches the snout on the same day. The remaining melt water is stored within the glacier which gets delayed and adds to later daily melt contribution (Martinec, 1970). In fact, the diurnal cycle of runoff also consists of a part of this continuing baseflow. Several studies based on the tracer experiments, isotope studies and analysis of the runoff distribution suggest that major contribution to baseflow resulted from continuous runoff from the accumulation area (firn area), continuous drainage from the glacier lakes, water filled cavities and ground water flow (Lang et al. 1979; Elliston, 1973; Collins, 1977, 1982; Stenborg, 1970; Tangborn et al., 1975). The baseflow dominated with melt water from the accumulation area has higher time of concentration as compared with melt water generated in the ablation area.

As melt season advances, in addition to variation in diurnal cycle of melt runoff, an increase in the baseflow also can be seen when continuous higher melting takes place over the glacier. Under higher and continuous melting environment, higher rates of recharge occurs to firn aquifer and an increase in streamflow is observed. The volume of the baseflow changes very slowly as compared with superimposed portion of the melt runoff. Elliston (1973) found that in the beginning of melt season (19th May, 1959) about one-sixth of the runoff volume was responsible for the peak on a steadily rising baseflow. It increased to about one-fifth after one month. Further when rates of ablation were at their highest, about two-seventh accounted for the peak. It was noticed that in the 8 weeks period when rate of ablation and the area of snow free ice were increasing rapidly, the amount of water discharged during the characteristic daily peaks increased about 16 times, but baseflow increased only about 8 times. The period considered in this analysis was almost dry, therefore, large sustained baseflow during the high peak flows were maintained by ablation. Further immediate reduction in the ablation rate influences peak value more significaltly as compared with baseflow. Observations on the Gornergletscher at 2580m showed changes in solar radiation due to clear skies to overcast resulted in reduced melt rate from 5.5 mm/hr to less than 1.5mm/hr in the early afternoon. It provided an immediate reduction in the peak of daily discharge, but very little effect on the sustained baseflow.

In the glacierized basins the diurnal fluctuations are not very much pronounced in the beginning of melt season due to percolation of melt water through snowpack. As the melt season progresses time-lag is reduced due to faster runoff from the exposed ice surface, reduction in snowpack area and depth. The reduction in time-lag is caused by the progressive development of drainage network with melt season. Such development of drainage network provides a faster response of melt water in the mid or late melt season. Its effect is reflected in the diurnal variation glacier melt runoff. Therefore, in the later part of ablation season diurnal fluctuations are more pronounced and follow fluctuations in available energy for melting. The time of peak flow in the daily rhythm occurs earlier in the day as summer progresses.

Generally minimum runoff near the snout of glacier is recorded in the early hours of morning (between 7 and 10 a.m.) and maximum in the late afternoon or evening (between 3 and 6 p.m.). The rising limb of the hydrograph is always steeper than the recession limb and peak of glacier melt is lagged by few hours after the time of maximum solar radiation.

In the basins which experience only seasonal snow, the total annual runoff cannot exceed the total annual precipitation. But the annual runoff from the glacierized basins may be either less or greater than annual precipitation due to addition of precipitation to the glacier mass or release of additional mass from the glacier depending on the meteorological conditions in the corresponding years.

4.2 Delay of runoff

The occurrence of maximum streamflow in the glacierfed rivers in the late afternoon or evening suggests that a major part of the melt water produced during the day period reaches the snout within a period of few hours. The storage characteristics of the glaciers are responsible for delayed response of melt water generated over the glacier surface into runoff. Elliston (1973) suggested that a large portion of melt water, possibly half, spends more than a day in the glacier. The magnitude of delay in response is a compound effect of ablation and accumulation area of the basin. The major delay factors appear to be the time of season, thickness of snow and distance of travel. The delaying response of the glacier also changes with time.

A comparison of diurnal behaviour of glacier melt runoff corresponding solar radiation can be easily considered for demonstration of delaying characteristics of the glaciers (Fig. 2). The time-lag between peaks of melt runoff and radiation/ tempterature indicate travel time for water from its point of generation on the glacier to the discharge measuring site. Generally, there is time-lag of few hours between maximum melt and maximum runoff at the snout. In order to obtain a clearer picture a hydrograph and solar radiation/temperature patterns are needed for non-rainy periods. For this purpose, melt runoff exclusively from the study glacier is needed just near the snout to exclude the impact of time taken by the water to travel from the snout to gauging site and also to eliminate any possible contribution from other sources within the reach from snout to the discharge measuring site. Evidently, streamflows for clear weather days observed nearer to the snout of glacier are considered more appropriate for determination of time-lag. In case gauging site is far in downstream from the snout, then it is very difficult to know the contribution from the study glacier because other streams join the glacier melt stream.

The structure of the hydrological system of a glacierzed basin through which melt water or rain water is routed to the outlet of basin is complex. The factors which make this system complex are the existence of storages within snow and glacier ice and influence of changes occurring in storage as snow undergoes metamorphism to firn and subsequently glacier ice. The melt water takes much time to appear as runoff in the beginning of melt season as compared with mid or later part of melt season. In the beginning of melt season, thermal and hydraulic retention capacity of snow over the glacier surface also form the part of storage and are to be satisfied. Melt water appears as runoff after satisfying these requirement of snow/firn.

The average basin time-lag of a glacier is a combined characteristic of the ablation and accumulation areas. Golubev (1973) suggested that control of the firn area on stream flow is greater than that of glacier tongue, and the basin lag of the firn area is approximately ten times longer. This difference is due to the fact that runoff from glacier tongue attributes to day peaks and the basic flow of the hydrograph is a result of runoff from the firn area. In order to compute and compare the time-lag from the ablation and accumulation areas, the recession characteristics are to be examined. The time-lag for the accumulation area is higher than the ablation area because response of runoff from the ice

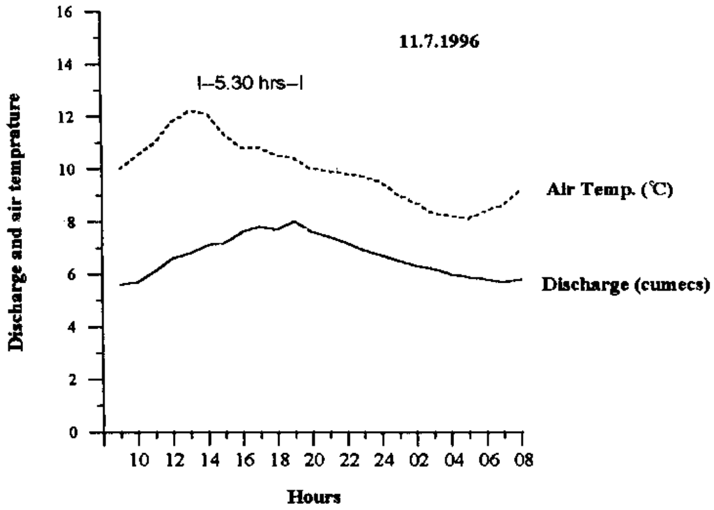

Figure 2: Diurnal variation in discharge and temperature observed at the Dokriani glacier melt stream gauging site

tongue is faster than the runoff from firn area. The impervious ice surface and negligible ice roughness of ice channels contribute to fast runoff of melt water. The water caught by the crevasses also move fast during the ablation season because drainage system within the glacier is well developed during this period.

Based on 8 small and medium glaciers, Golubev (1973) established the following simple relationship between average time-lag and active drainage area of glacier (Fig. 3),

$$\tau = 3.8 \log_{10}(S+1) \qquad (1)$$

where τ is the average time-lag of melt water in days and S is active drainage area in km^2. The glacier area with temperature above 0°C can be considered as active drainage area of the glacier. In the beginning and end of the melt season, the active drainage area may be lower than the whole area of the glacier due to subfreezing temperatures in the upper part of the glacier. During summer period the whole area of the glacier becomes active drainage area. Temperature observed at lower altitude with appropriate lapse rate can be used to estimate the active draiange area of the glacier.

The equation for the mean recession curves can be approximately written as:

$$Q_t = Q_o\, e^{-t/\tau} \qquad (2)$$

where Q_t and Q_o are the discharges at time t in the beginning of recession at time $t=0$, respectively. τ is the average basin time-lag of the glacier. It can be easily noticed from this equation that 90% of the initially stored water is drained within $t=2.3\tau$.

Golubev(1973) attempted to correlate average basin lag, τ, glacier tongue lag,τ_i and firn lag,τ_f. In case there is no inflow, runoff from the glacier Q depends directly upon the volume of water stored, W, in the glacier, and changes of the volume dW corresponds to the changes of discharge Q:

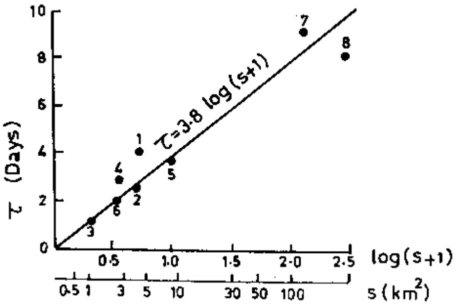

Fig. 3 : Dependence of the mean time-lag of melt waters from the glacier on its active drainage area. 1. Karabatkak (Tien-Shan), 2. Dzhankuat (Caucasus), 3. Igan (Urals), 4. Garabashi (Caucasus), 5. Bol'shoi Aktru (Altai), 6. Maliy Aktru (Altai), 7.Zeravshanskiy (Pamir-Altai), 8. Fedchenko (Pamirs).

$$dW = \tau \, dQ \tag{3}$$

or

$$\tau = dW/dQ \tag{4}$$

where τ is the average basin lag. Usually the curve $W = f(Q)$ is quasi-linear or linear, then

$$\tau = W/Q \tag{5}$$

The accumulated volume W is formed by the water stored in tongue W_i and the water stored in the firn, w_f,

$$W \doteq W_i + W_f \tag{6}$$

Using equation (5) for tongue and firn area, the accumulated volume can be approximately expressed as:

$$W_i = \tau_i \, Q_i \tag{7}$$

$$W_f = \tau_f \, Q_f \tag{8}$$

Therefore,

$$\begin{aligned} \tau &= W/Q \\ &= (W_i + W_f)/Q \\ &= (\tau_i \, Q_i + \tau_f \, Q_f)/Q \\ &= \tau_i \, (Q_i/Q) + \tau_f \, (Q_f/Q) \end{aligned} \tag{9}$$

or

$$\tau_f = [\tau - \tau_i \, (Q_i/Q)]/(Q_f/Q) \tag{10}$$

Determination of Q_i and Q_f is possible using tracer techniques or analysis of hydrograph for clear weather days. τ, and τ_i can be obtained using equation (2), then τ_f, can be obtained from equation (10).τ can also be obtained from equation (1).

5.0 IMPACT OF PRECIPITATION ON THE RUNOFF RESPONSE

The precipitation in the form of snow deposits over the glacier surface increasing the mass of the glacier. The response of rain depends on the snow coverage and melting conditions of the glacier. During early summer period, the glacier surface is fully covered by snow and all the precipitation falling as rain is absorbed in snow cover. Continuous depletion of the standing snow exposes the ice surface slowly and slowly. The exposition of glacier ice area starts from the terminus/tongue of the glacier and proceeds upward as the season advances. It is clear that rain will provide a quicker impact on runoff when maximum glacier ice area is exposed and the depth of snow over remaining body is minimum which reduces retention capacity of liquid precipitation. Such conditions are observed in the later part of the ablation period. In addition to this, the internal drainage of the glacier is well developed by the late ablation period and helps in faster response of rain occurred over the glacier. It is clear that large rainfall events in winter and spring have little or no effect on runoff because more or less whole amount of rainfall is soaked and retained in the snowpack only. Whereas in the autumn smaller amount of precipitation also produced significant changes in the runoff peaks. It is for this reason that major rain induced flood events are observed in the second half of the ablation period.

The summer snowfalls greatly reduce the ablation of glacier because absorption of solar radiation is immediately reduced due to higher albedo of snow. It results in reduced runoff and diurnal rhythm is almost suppressed. The melt water stored in the snowpack recesses slowly. The decline of baseflow persists over several days depending upon the depth of fresh snow and weather conditions. After depletion of fresh snow, melt runoff follows the increasing trend.

6.0 STORAGE AND DRAINAGE CHARACTERISTICS OF THE GLACIERS

The melt water is stored at various locations in the glacier like firn pools on the ice surface, crevasses, englacial pockets, subglacial cavities, the moulin conduit network, englacial or morainic lakes etc. Storage of water at different locations can be considered as presence of small reservoirs in the glacier body. Water supply to these reservoirs is provided intermittently by melt water from the glacier surface. The stored water continuously drains out of the glacier through its snout. The rate of discharge of outflowing water is controlled by the hydrostatic pressure in the reservoirs. During the melt period when melting increases, some amount of melt water fills up the glacier storage resulting in lesser outflow than inflow to the glacier. Further, when melt rate decreases the water accumulated in glacier storage also contributes to the outflow resulting in higher out flow than inflow. When inflow to the glacier is ceased, the outflow fully depends on the drainage from glacier storage. For example, in the glacier fed stream winter flow is derived from the water stored in the firn aquifer and ground water contribution. Because of no further melt water input to the glacier the streamflow exponentially decreases. Seasonal variations in liquid water storage in the glaciers clearly imply a change in the hydrologic characteristics within the glacier during the season (Mathews, 1964, Tangborn et al., 1975). It is also important to note that drainage of runoff from the glacierized basin reflects not only energy supply variations but also changes in source areas exposed to melting.

Meltwater generated at different locations over and within the glacier surface follows different routes of travel before emerging out from the terminus. The distinct ways of travel are basically because of passage of meltwater through different mediums. The glacier is composed of snow, firn and ice with differences in their physical properties. Distribution of these materials in and over the glacier determine the drainage properties of the glacier. The following three zones of flow governing the operation of whole drainage system can be easily distinguished on a glacier:

i) the vertical percolation of melt water and rain through snowpack and firn into saturated zone.

ii) the flow in melt water channels on the glacier surface or in pipes within the snowpack or the glacier.

iii) the lateral, more or less horizontal flow in the saturated zone at the bottom of snowpack and over impermeable ice.

There are little changes in storage and travel time on the daily basis in the glacier because vertical unsaturated flow in the snowpack, the turbulent flow in surface channels and the internal network of pipes in glaciers do not change over short intervals. But on the seasonal basis, there are significant changes in the draining network affecting hydrological response of the glacier. In the beginning of melt season when whole glacier surface is covered with snow, the response of the system is clearly slower. As the melt season advances, the response becomes faster. After the high discharges in July the characteristics of the system do not change significantly until September. At the end of melt season whole drainage pattern gradually becomes constricted by freezing of melt water.

6.1 Movement through snow and firn area

Because of availability of firn throughout the melt season in the accumulation area of glacier, a considerable amount of melt water is stored in the firn aquifer. The magnitude of stored water depends on the areal extent and depth of firn area. Evidently amount of stored water varies from year to year. Field investigations carried out over different glaciers support this hypothesis (Oerter and Moser, 1982; Schommer, 1976, 1978; Lang et al, 1977 and 1979). The recharge of firn aquifer changes with melt season due to changes in melt rate. The melting conditions determine the recharging area of the firn aquifer. For example in the beginning of melt season melting takes place only over the lower part of firn aquifer and therefore recharging of only lower part of firn aquifer takes place. At times when melting occurs over the whole glacier surface, recharging also takes place over whole firn aquifer. It is to be noted that depth and extent of firn area also reduces because of melting as melt season progresses and porous system varies with time due to changing conditions in the snowpack. However, an accurate estimation of stored water in the firn aquifer is a difficult task, but becomes very important when hydrological method is applied for determination of mass balance of glaciers.

The flow through the snow can easily be considered analogous to the flow through unsaturated porous media. The permeability of this media depends on the water saturation and therefore flow in this unsaturated media will vary because of continual changes in the amount of water saturation at any level. Presence of ice layers and lenses influences the movement of melt water through snow. Firn layers exist between snow and ice mass and flow through the firn is not well understood. However, it is clear that rate of movement of melt water through firn layers will be lower than that of snow because of higher density and lower permeability of firn. In the beginning of melt season, snow and firn layers are at below freezing temperature, and melt water is generated over the glacier surface. This melt water percolates to some depth and freezes there. Sub-zero ice temperatures have a remarkable influence on the superficial or internal drainage only during a short period at the beginning of the melt season. In case melt water is concentrated slightly at one place due to topography, then heat released due to freezing of the melt water warms the snow existing around the freezing point. In this process, a "dimple" is formed on top of cold layer and it provides an easier path for further percolation of melt water at such locations rather than other ones. Thus, melt water passes through the cold layers. Development of peculiar vertical channels or pipes in the snow and firn layers in the temperate glacier takes place due to this "drilling" process.

Direct tracing with radioactive substances may provide travel times and in case there are more than one frontal streams, it may give indications of drainage area separation. There are various studies carried out on the isotopic composition of firn on glaciers (Dansqaard, 1961, Ambach and others, (1968a). It was pointed out by Ambach and others (1968b) that the differences in tritium content in different parts of a glacier could be able to provide information on the delay characteristics of melt water into runoff, like summer melt water into winter runoff. Such studies on different times during the whole recession period are considered helpful to give an indication of the correspondence between the drainage system of the firn area and that of the tongue.

The major factors controlling the infiltration of melt water through snowpack are the intensity and duration of melting, thermal conditions of snowpack, initial structure of the snowpack and its changes along the vertical profile. Based on the infiltration properties in the firn basins, snowpack before the beginning of melting can be delineated into upper and lower layers. The upper layer consists of almost homogeneous fine-grained snow with lower density and higher permeability. The lower layer with old snow contains snow with higher density, which is responsible for lower permeability of melt water. The presence of ice lenses is very common feature in the old snowpack whose amount and thickness increase with depth. Monitoring movement of dye showed very different infiltration rate in the upper and lower layers due to difference in physical properties of snowpack through out the melting period continuous redistribution of water storage takes place in the pack. Infiltration front penetration on Mount Elbrus shows that in the upper part the average rate was observed 4.5 cm/day which smoothly increases with depth reaching its maximum about 25 cm/day at the bottom of snowpack (Bazhev,1973). At the interface of firn the rate was reduced significantly and dropped to about 2 cm/day. Further down infiltration rates decreases and becomes more variable because of occurrence of ice layers and snow lenses. Table 2 shows the results obtained in various mountain glacial regions.

Table 2: Observed infiltration rate in different glacial regions (Bazhev,1973)

Region	Total depth of infiltration (cm)	Average rate of infiltration (cm/day)	Thickness characteristics
Spitsbergen (Lomonosov plateau)	200	5	snow
Novaya Zemlya (central part)	600	7.5	snow and firn
Central Caucasus (Elbrus)	500	4.5	snow and firn
Western Pamir (Lednik Medvezhiy)	280	5.5	snow

6.2 Movement through ice area

In the ablation area where glacier ice is exposed melt water travels through conduits. Water flowing in some conduits joins the vertical deep holes in the glacier body which are known as "moulins". Some moulins extend up to the bottom of the glacier and water entered these moulins reaches the glacier bed within no time. Stored water appears to be in dynamic interaction with changes in conduit capacity. The size of water conduits enlarges slowly with an increase of water input. The network of surface melt water channels becomes more articulated and progresses further up glacier as a result of slushing out and melting.

Injections of tracers, such as fluorescent dye, salt or radioactive isotopes on the glacier surface and its monitoring at snout are used to assess the travel time of melt water occurring at the glacier surface to reach the terminus. Experiments have indicated water flows very fast, in the order of kilometers/hour through open channels and moulins. But the water movement through the snow and firn area has been found to move at least two order of magnitudes slowly. Isotopic and melt water chemical composition studies from Alpine glaciers suggest that ice-melt water drains through conduits in a few hours (Behrens et al, 1971; Collins, 1979), whereas water from the firn takes longer time because water from the firn percolates slowly, being stored in the firn aquifer enroute to conduits (Lang et al, 1977). Integration of melt water stored in the firn aquifer depends upon very much on the state of connection from firn area to conduits, on the conduit network development and on the length of the recession period.

Some of the melt water from the exposed ice area reaches the outlet of glacier through internal drainage. Melting of glacier surface and collection of superficial runoff are the basic conditions to generate the internal drainage through the glacier body. For the initiation of internal drainage courses, the following two possibilities are suggested by Stenborg (1973).

(i) Development of drainage courses in connection with pre-existing vents of glacier tectonics origin or in connection with vents of that kind arising contemporaneously or subsequently. Such vents are expected in the lateral positions because of relatively high shear strain rates, low thickness of ice and water supply through oblique superficial crevasses.

(ii) Development of drainage courses due to standing water

Such conditions allow the water to penetrate down into the glacier body which is further drained off through internal drainage network. Because melting does not take place throughout the year, therefore, development of internal drainage system is restricted to the small part of the year. Main parts of the drainage courses are studied indirectly because there are so many practical difficulties involved in direct observations.

The upper parts of the internal drainage course are determined by the crevasses during their development. Crevasses play an important role in further distribution of surface runoff resulting in immediate further drainage of water. The oblique tensile crevasses, forming a series on each lateral half of a glacier tongue, are considered very important in terms of influence on internal drainage. At zero longitudinal stress these crevasses form straight lines at an angle of 45°to the margin and approaches the central line of the glacier (Nye,1952). The compressive longitudinal stress changes the form and direction of these crevasses. Under compressive longitudinal stress, the crevasses are formed in a way that central part of the glacier surface is not covered by the crevasses. Consequently, in the central part only surface runoff occurs. Stenborg (1973) found that on both sides of the central strip, there are zones of favourable conditions required for the development of glacier mills having very fast draining off characteristics. In general, these mills are developed at the outer extensions of crevasses from the bordering area (Fig. 4). It was reported that mills in these positions survive for a greater period than the mills developed in other location of the glacier.

The development of systems of glacier mills in the superficial oblique crevasses is controlled by the melt water supply, structure of ice and time. The mill system implies a deflection of the drainage with its main direction obliquely towards the lateral margin of the glacier. These mills are developed in series and number of glacier mills developed simultaneously in one crevasse depends on the intersecting structure, ice-surface topography and crack formation during the period of superimposed ice. Stenborg (1973) observed five to seven mills on the Mikkalglaciaren, Sweden and the life of mills was observed to be normally 3-7 years. However, determination of extreme life span of these mills is very difficult without long series of direct observations, but no clear proof of mills with an age of more than 10 years was found by indirect methods.

The detailed study on the development of glacier mills have indicated that a mainly simultaneous development of the different mills occurs along any crevasse. These mills offer

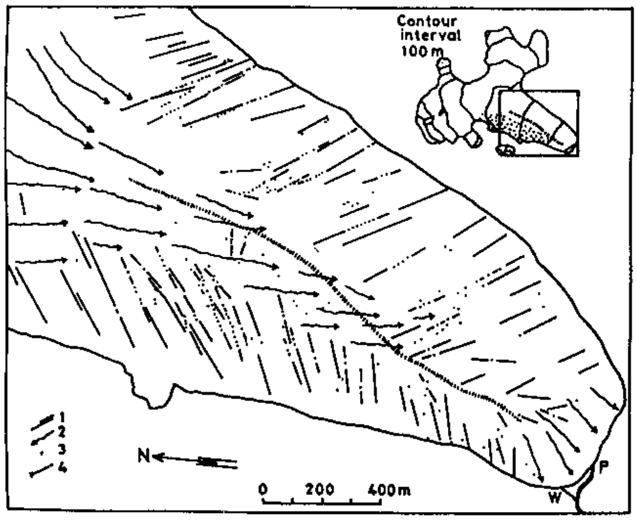

Fig.4: Generalized map of the tongue of Mikkaglaciaren, comprising observations from the years 1956-58 and 1961-66. The following symbols are used: (1) crevasses, (2) surface run-off, (3) glacier mill, (4) boundary between areas of crevasse striking east and west, respectively. Part of the surface run-off of the western area terminates in the drainage structuresof the eastern half. The stippled area on the inset shows the ablation area supplying the western frontal stream (W).

a natural drainage course and are interconnected along the crevasse. Stenborg (1973) observed the greatest mill depth to be 39m on Mikkaglaciaren. Once water has entered the mill, it has either to move laterally to strips of thinner ice or to penetrate vertically through uncrevassed ice. It was also reported that any mill reaches its maximum ice depth within first one or 2 years, and after that it does not deepen vertically during the rest period of mill's life.

The movement of melt water through ice is relatively poorly understood: Earlier glacier ice was considered as impermeable because liquid water was thought to be concentrated in small tetrahedra at four grain intersections (Steinemann, 1958). However, recent investigations have explained the possibility of water moving through glacier ice along a complex three dimensional network of tiny prisms along three grain intersections. The volume of water travelling through the ice is very little. For example, water arriving at the bottom of glacier over a period one year through this route is about equivalent to 1m thick layer of ice (Lliboutry, 1971; Nye and Frank, 1973). Raymond and Harrison (1975) determined the upper limit of annual water flux reaching glacier bottom through intraglacial seepage to be about 0.10 m per year, with corresponding velocity of about 60m/year.

6.3 Movement of melt water under the glacier

After penetration of water to the bed of the glacier, it joins the existing conduits carved in the ice at or near the ice/bedrock interface and flows towards the terminus. In the lower and upper part of the glaciers, a separate drainage network exists, but normally one single main stream emerges out from the glacier. Sometimes more than one stream are also observed. The location of streams is governed by the topography of the bed and may change from time to time.

It is generally accepted that in winter conduits at the glacier bottom start closing and water is sealed off in small cavities and channels, especially at the base of the glacier (Tangborn et al. 1975; Lang et al., 1977). As the ablation season starts, water storage in the snowpack, firn aquifer increases and results in high water pressure in the glacier body. A rise in the water pressure produces higher runoff and widening of pipes and channels take place.

Consequently, in summer internal hydrological system enlarges both in capacity and extent. Drainage of water stored in sub-glacial, en-glacial and supraglacial locations increases with progressive network. Improved efficiency of throughflow progressively reduces the runoff delay in summer (Elliston 1973; Lang, 1973).

7.0 RUNOFF, MOVEMENT AND DRAINAGE

Changes in the physical characteristics of the glacier in the beginning of melt season and during the melt season are responsible for changes in the drainage characteristics. Superficial and internal drainage, glacier movement and runoff from a glacier are mutually correlated. Some investigators (Paterson, 1964; Oelsner, 1967) established correlation between glacier movement and melting (air temperature). Such relationships were developed both for short periods and for the main seasons. Observations indicate that maximum glacier movement was found during the late spring and early summer when melting rate is less. The glacier movement decreased in the month of July and August when melting rate is higher. Early summer period is characterized by less melting, small amounts of runoff and high glacier movement. At this time impermeable glacier surface is fully covered by snow and superimposed ice and internal drainage intakes remain closed. Under this condition storage of water is increased in and under the glacier which accelerates the glacier movement because of high hydrostatic pressure.

Accumulated snow and firn over the glacier surface gradually disappears owing to melting. Consequently opening of most of the earlier drainage connections by melting of snow and increased crevassing results in faster draining of stored and generated water. Further, an increase in the drainage rates and development of better draining network reduce the amount of temporarily stored water in the glacier. This can be considered one of the main reasons for the decrease of glacier movement during the later part of summer. In other words, development of drainage courses will permit higher rates of runoff recession and temporarily stored water will be gradually drained and glacier ice velocity will thereby decrease during the rest of the summer. The decrease in glacier velocity is otherwise difficult to explain during the period of the summer when melting rate is highest over the glacier surface.

The glacier movement is found responsible for the destruction of the drainage connections on both the micro and macro scales. Deformation of the channels sometimes causes blockage or release of water stored water. The release of water may or may not be discernible on the stream flow records because it depends upon the amount of released water and streamflow in the melt stream at that time. The influence of the glacier movement on the drainage conditions can be described as the reverse effect. Increased velocity during the first part of summer results in frequent formation of crevasses accelerating the drainage from the glacier. This explains that maximum runoff occurs after the period of maximum ice velocity.

Similar investigations have been attempted to study the influence of melting on the movement of glacier. The availability of water during the melt period provide water supply to the inner and bottom parts of the glacier which influences the glacier movement. Such observations were found to be very important in connection with glacier-sliding theories (Weertman, 1957, 1964; Lliboutry, 1959, 1968).

8.0 ASSESSMENT OF WATER STORAGE IN AN ALPINE GLACIER

Seasonal changes in the water stored within the glacier can be estimated using information on precipitation, discharge and mass balance. Tangborn et al. (1975) used such information for South Cascade Glacier, Washington, USA and reported an increase in storage during spring to a maximum volume in early June. The minimum volume of melt water retained in the glacier was observed in late September. Most of the studies related to water storage within the glaciers have been largely concerned with seasonal variations in runoff delay (Collins, 1982).

An assessment of the volume of water stored in the glacier can also be made using actual discharge and potential melt computed from energy balance approach. Using this methodology, Stenborg (1970) found that during the early melt season about 25% of the total annual discharge from the Mikkaglaciaren, Sweden was retained in the glacier. This water was released in the middle part of summer. A reduction in retention and runoff delay is observed as the melt season advances. Sequential changes in diurnal variations of runoff, as indicated by variations of monthly average recession coefficients (Ellison, 1973; Lang, 1973), confirm a reduction in runoff delay.

Collins (1982) estimated actual quantities of liquid water retained in a glacier utilizing only discharge measurements. Recession characteristics of the hydrographs have been used for this purpose. Analysis of recession curves was also found to be very useful in separating quick flow from the baseflow and to understand the seasonal behaviour of aquifers (Webber, 1961). Sudden termination of ablation because of snow event may interrupt immediately the periods of either increasing, steady or already recessing flow. Recession characteristics are therefore strongly dependant on the melting conditions in the period preceding the depletion. In events of suppression of ablation, like summer snowfall, a declining flow is derived principally from stored melt water. Because there is no input to the system, recession of flow takes place until either total stored water is exhausted or further input is received by the system. Collins (1982) studied the water storage in Gornergletscher, Switzerland from hydrographs of recession events. Recession curves resulted from summer snowfall during ablation period (June-September) in the years 1970-79 were identified. Semi-logarithmic plot of depletion events of the Gornera (Gornerqletscher melt stream gauging site) for different dates are shown in Fig. 5a. Total measured discharge from the glacier between starting ($t=0$) and end of recession provides a minimum estimate of internal storage of water at $t=0$.

The melt water appearing at the snout of glacier arises from two main reservoirs: runoff derived from ice melt in the ablation area routed rapidly through the moulin conduit system, and water derived from the firn in the accumulation area, passing more slowly to the conduits. Semi logarithmic plots are considered very useful to separate the different curves, if any, with different slopes (Fig. 5a). For example, in the curve 1, three arcs with different decreasing rate are visible. The discharge declines with higher rate from t_o to t_1 as compared with arc from t_1 to t_2. The last arc show zero gradient. Different arcs in the same recession hydrograph can be interpreted on the basis of contribution of water from different reservoirs. The arc from t_0 to t_1 probably reflects the draining of a "fast" reservoir of water derived from ice melt. The middle arc from t_1 to t_2 represents the drainage from a "linear" reservoir represented by the firn aquifer. The third section $t > t_2$ appears only in the long recession events and suggests limited base flow supplied by subglacial ground water.

An Assessment of stored melt water can be made using following methodology. Considering the glacier as a linear reservoir, discharge is a linear function of the stored volume of water at time t, i.e.

$$Q(t) = k\, S(t) \tag{11}$$

where k is the recession coefficient or the storage coefficient of the reservoir representing the rate of drainage of the reservoir. The water balance of the glacier at time t can be given as

$$I(t) = Q(t) + ds/dt \tag{12}$$

where I(t) is the total input in the form of melt water from ablation and accumulation area of the glacier at time t. Eq.(11) and (12) provide,

$$I(t) = Q(t) + 1/k.\ dQ/dt \tag{13}$$

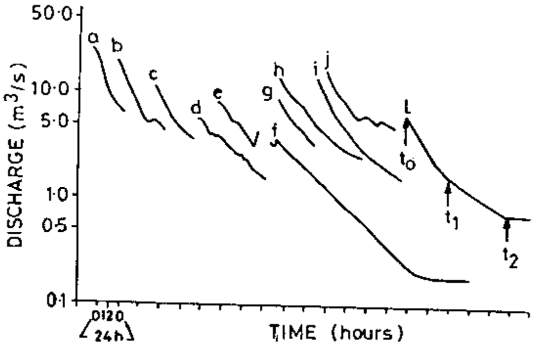

Fig.5a: Semi-logarithmic plot of depletion curves of the Gornera during different recession events: (a) 8-10 August 1970, (b) 20-23 August 1970, (c) 29 June-1 July 1971, (d) 10-13 June 1972, (e) 3-5 September 1972, (f) 14-25 September 1972, (g) 7-9 June 1973, (h) 20-25 June 1973, (i) 22-27 August 1975, (j) 27-29 August 1979, (l) 21-26 September 1979. In curve l, t_0=time of commencement of depletion, and t_1-t_2 is the linear section of the curve (Collins, 1982).

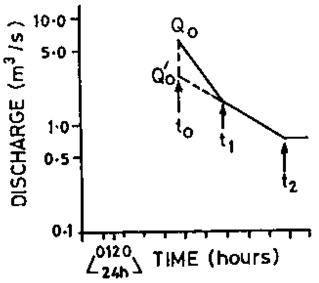

Fig.5b: Estimation of initial discharge from the linear reservoir through extrapolation of linear reservoir recession line.

In case I=0, due to snowfall or any other reason, Eq.(13) can be written as

$$Q(t) = Q_0 e^{-kt} \qquad (14)$$

where Q_0 is the discharge t=0, i.e. at time when recession starts. Eq. (14) represents a characteristic depletion function describing the exponential decay of discharge. Eq.(14) can also be represented as

$$\log_e Q(t) = \log_e Q_0 - k\ t \log_e \qquad (15)$$

Recession coefficient for each recession event can be obtained graphically by fitting equation (15) for the semi-logarithmic plots of discharge (Fig. 5a). Equation (15) describes a straight line with a slope equal to - k $\log_e$. Therefore, value of k can be derived from this method.

In order to quantify the value of initial discharge from the linear reservoir, Q_0', for the event like curve 1, one has to extrapolate the line to the intercept t=0 as shown in Fig. 5(b). Thus, initial storage in the linear reservoir, S_0, can be determined using values Q_0' and k. Following equation (11)

$$S_0 = Q_0'/k \qquad (16)$$

Water stored in the fast reservoir, R_0 can be obtained as

$$R_0 = \int_{t_0}^{t_1} [Q_0(t) - Q_0'(t)]\ dt \qquad (17)$$

Total storage of liquid water in the glacier is obtained by R_0+S_0. Details of water storage characteristics on the Gornergletscher for recession periods in different ablation seasons are shown in Table 3. Results are presented only for events for which separation of fast and linear reservoirs could be possible. It can be noticed that linear reservoir contained between 63 and 96% of estimated total water storage in the glacier at the beginning of recession.

Table 3: Water storage characteristics of the accumulation on Gornergletscher for recession periods in the ablation seasons of 1970-79.

Period	Total initial storage in slow and fast reservoirs	Initial storage in slow reservoir	Total measured discharge as percentage depletion of total initial storage	Recession coefficient
	(S_o+R_o) $(10^6\ m^3)$	(S_o) $(10^6\ m^3)$	(%)	k(day^{-1})
8-10 Aug. 1970	2.78	1.91	60.4	0.65
14-22 Sep. 1972	0.79	0.70	94.9	0.46
7- 9 Jun. 1973	1.32	1.20	63.6	0.60
20-25 Jun. 1973	2.61	2.02	80.7	0.38
18-20 Jul. 1974	1.38	1.32	55.8	0.44
22-27 Aug. 1975	1.94	1.34	81.0	0.36
15-18 Sep. 1976	0.34	0.32	74.7	0.54
27-30 Sep. 1978	0.86	0.77	70.1	0.48
27-29 Aug. 1979	2.74	2.38	63.3	0.49
21-26 Sep. 1979	1.20	0.75	86.7	0.42

After recession the discharge was found to be considerable, as much as 35% of Q_0. The depletion of calculated total initial storage ranged about 56 to 95% with no discernible temporal pattern (Table 3). It was also argued that in spring probably much of the stored water is not integrated with flow. Therefore, total quantity of stored water estimated using hydrograph recession approach in this period may be lower. However, in the summer period, when stored water is integrated, the accuracy in calculation increases.

Generally, quantities of melt water stored in linear reservoir (firn aquifer) during June-August were at least double than the quantities calculated for the months of September. Normally there is tendency that larger volumes are discharged in the recession at the beginnings of ablation season and smaller in the quantities at the end of melt season. It was found that slow rates of recession usually interrupted the complete recession and changes in weather conditions allowed ablation resulting in an increase in discharge. For Gornergletscher the values of computed recession coefficients ranged from 0.36-0.65 day^{-1} indicating the variations of the delay of runoff. Lang (1973) calculated recession coefficients from monthly mean of falling segments of daily flow variations for each of four years. These values can be approximated as k in this study. Recession coefficients for each month, averaged over 4 years period increased from May to September, from 0.28 to 0.44 day^{-1}. However, mean recession coefficient derived from monthly aggregated data do not represent the major characteristic of internal storage in the alpine glaciers.

9.0 GENERATION OF EXTREME STREAMFLOWS

The rain-induced floods are often recorded in the high alpine regions. Flash floods are very common features in the mountainous areas because of greater slopes and high impermeability of rocks. In general high streamflow in the glacierized basins are produced primarily because of the following three events individually or in combination:

- intense rainfall
- higher melt rate
- outburst of glacier-dammed lakes

9.1 Intense rainfall

In the beginning of melt season when most of the glacier ice is covered by deep snow, most of the rain is soaked by the snow cover and intense rainfall cannot generate high streamflows for the glacierized area. But the high intensity rainfall over the glacier in the mid or later part of melt season is very much capable of producing floods. The glacier ice is exposed to its maximum at this time allowing very fast response of the rain over this part of the glacier. Moreover, no losses occur from the rain due to impermeable ice surface. Consequently, flood situation arises under intense rainfall conditions. The upper part of the glacier still has the delaying characteristics because of availability of snow there. It is to be noted that during rainfall events, the melt rate is reduced significantly due to reduction in solar radiation under cloudy conditions.

9.2 High melt rate

Sometimes flood situation may occur because of higher melt rate of ice. Probability of such events is higher when major part of the glacier ice is exposed due to ablation of accumulated snow over it. This situation allows maximum absorption of solar radiation by the glacier causing higher melt rate over all the elevation zones of the glacier simultaneously. The presence of debris or dust of appropriate depth over exposed glacier ice increases the melt rate and helps in producing high streamflows.

The probable maximum heat flux during the summer days can produce the maximum melt rate up to about 10mm/hour, producing specific melt water of about 2800 lS^{-1}km^{-2} or 2.8 m^{3}S^{-1}km^{-2} from the lower part of glacier having exposed ice. Daily maximum point melt rates are reported in the range of 90-100 mm day^{-1}, with corresponding specific runoff 1100 lS^{-1}km^{-2} or 1.10 m^{3}S^{-1}km^{-2} (Gurnell and Clark,1987). Observed maximum specific melt runoff observed from few glaciers in the Alps is given in Table 4. It can be noticed that high melt rate events occur either in July or August when glacier ice is exposed to its maximum and heat flux is also high.

Table 4: Maximum specific runoff values observed at various glacier river basins (related to whole area of glacier)(Gurnell and Clark, 1987)

Details of the glacier and its location	Period
Hintereisferner (Austrian Alps, 15.45 km^{2}) (Lang, 1966)	10th July,1959 (period 1957-1959) Max. daily mean:640ls^{-1}km^{-2} (55 mmd^{-1}) Max. 2 hourly mean:950ls^{-1}km^{-2}
Vernagtgletscher (Austrian Alps, 9.3km^{2}) (Moser et al., 1983)	July,1976 (Period 1974-1982) Max. hourly mean:780 ls^{-1}km^{-2}
Aletschgletscher (Swiss Alps, 123km^{2}) (Emmenegger and Spreafico, 1979)	August (period 1965-1977) Max.daily mean: 688 ls^{-1}km^{-2} Max. instantaneous value:854 ls^{-1}km^{-2}

9.3 Outburst of glacier-dammed lakes

There are worldwide examples of severe flood occurrence due to outburst of the glacier-dammed lakes in the high altitude areas. The main reason for the creation of glacier-dammed lakes is considered the normal tectonics not allowing the drainage of water. Such conditions can be generated because of topographical position of the lake and the special conditions of ice movement. In general these lakes are emptied suddenly and create a havoc in the downstream.

Three processes namely accidental crevassing, buoyancy or ice flow due to pressure difference, are considered responsible for draining out the water from the ice-dammed lakes. The process related with ice flow due to pressure difference is discussed in detail by Glen (1954). It was pointed out that water will tend to spread equally in all directions along the bed. The emptying will take place under the ice "in the downhill direction" because enlargement in that direction will generate "increased pressure there relative to the other points". Such conditions are further elucidated by considering the characteristic of a hole in the glacier body. The maximum pressure difference in a hole that is deeper than the critical depth is found at its bottom. Under purely hydrostatic conditions and with isotropic ice, the flow would occur in an arbitrary direction from the deepest part of the hole. But, in the actual field conditions the direction is controlled primarily by tectonic weaknesses, ice anisotropy and local differences in ice pressure. Under such conditions the extension of the hole will take place more or less horizontally along the glacier bed than perpendicularly to the contours of the substratum.

10.0 STORAGE CHARACTERISTICS OF THE DOKRIANI GLACIER

To determine the storage characteristics of the Dokriani glacier, continuous monitoring of the glacier melt runoff was made. For continuous recording of flow an automatic water level recorder was installed at an altitude of about 4000 m very near to the snout of the glacier. For further analysis, hydrographs of clear weather conditions were analysed. If continuous hydrographs for clear weather conditions for few days are available, a better picture of the storage behaviour can be obtained. Consideration of clear weather days becomes very important for such analysis to arrive at accurate estimation of the glacier melt runoff. On the rainy days contribution from the rain is added to the streamflow and separation of this contribution is difficult. Moreover, on the rainy days when rain is observed near the base camp, depending upon the prevailing temperature conditions it is is likely that snow may occur in the upper part of the glacier. Under such conditions whole glacier surface does not necessarily contribute to runoff due to rain.

For the Dokriani glacier, the ratio of maximum runoff to minimum runoff was found to be 1.46,1.39 and 1.50 for 10th, 11th and 12th July, 1996 indicating a considerable streamflow in the channel during the night period. A major part of the runoff during the night time was received from the stored water in the snow and firn area of the glacier.

The diurnal flow which is superimposed over the baseflow has a major contribution from the ablation part of the glacier. Melt water from the accumulation area dominated by delayed response also contributes partly to the this flow. The contribution from the ablation area reaches faster to the glacier outlet through super-glacial and sub-glacial streams. Glacier melt runoff recorded for the whole melt season that changes in the baseflow are very slow in comparison to the diurnal cycled flow. It can be understood from the behaviour of melt water response from the various parts of the glacier. Broadly contribution in the streamflow arises from two areas namely ablation area and accumulation area. Depending on the response of melt water from these areas they can be designated as fast and slow reservoirs, respectively. Sudden diurnal variations in the melt rate over the glacier influence the runoff from the ablation area immediately while runoff coming from the water stored in the accumulation area has little immediate impact of such events unless those are continues for several days.

Analysis of hydrograph for period from 10-12 July indicated that in about middle of July maximum glacier melt runoff near the snout was recorded between 1800 and 1900 hours whereas minimum flow was obtained between 0700 and 0800 hours (Fig. 6)

For clear weather days with temperatures above freezing point, a strong diurnal variation in the runoff was observed owing to diurnal cycle of solar radiation/air temperature. A comparison of patterns of diurnal variations of air temperature and runoff suggests an average time-lag of about 5 to 6 hours between maximum temperature and maximum runoff (Fig. 6). It implies that melt water occurred in the ablation area takes about 5 to 6 hours to appear as runoff at the gauging site. This time-lag is expected to reduce as melt season progresses because of improvement in drainage network of the glacier.

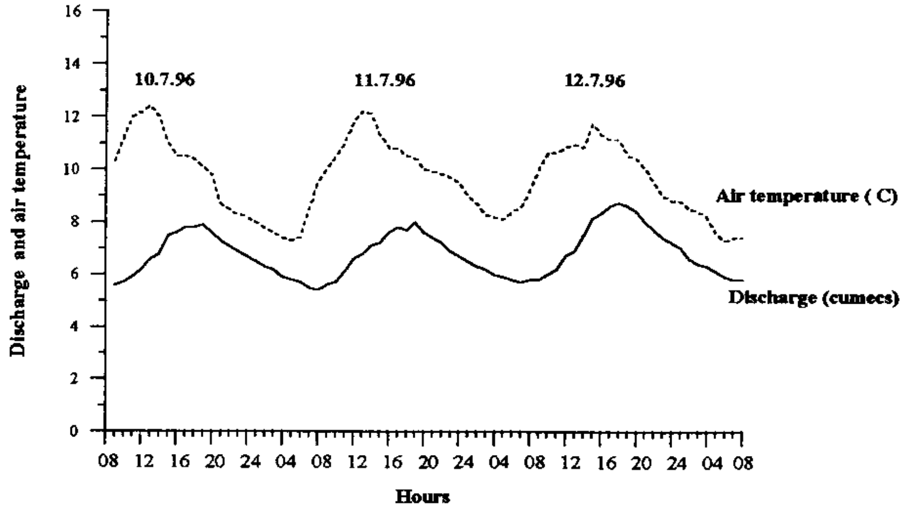

Fig. 6: Diurnal variation in discharge and air temperature observed at the Dokriani glacier melt stream gauging site

11.0 CONCLUSIONS

Basin flow characteristics of the glacier melt runoff are described. They include melting environment and arrival of melt water in the melt stream through various parts of the glacier. There are some basic differences in the flow characteristics of ice free basins and partially or fully glacierized basins. A considerable amount of runoff is received in the glacier melt runoff stream during the night period due to melt water storage characteristics of the glaciers. It results in a low value of the ratio of maximum and minimum streamflow from the glacier. For the Dokriani glacier this value was determined to be 1.46,1.39 and 1.50 for 10th, 11th and 12th July, 1996, respectively.

Analysis of hydrograph for period from 10-12 July has shown that in about mid July maximum glacier melt runoff near the snout was recorded between 1800 and 1900 hours whereas minimum flow was obtained between 0700 and 0800 hours. The mean travel time of melt water from ablation area was determined to be about 5-6 hours. The time-lag for the melt water from the accumulation area would be several times higher than this time-lag. Baseflow varies very slowly in comparison to the diurnal flow from the glacier.

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