ECOHYDROLOGICAL STUDIES OF DOKRIANI GLACIERISED BASIN, GARHWAL HIMALAYA, UTTARANCHAL

Thesis submitted for the degree of

Doctor of Philosophy

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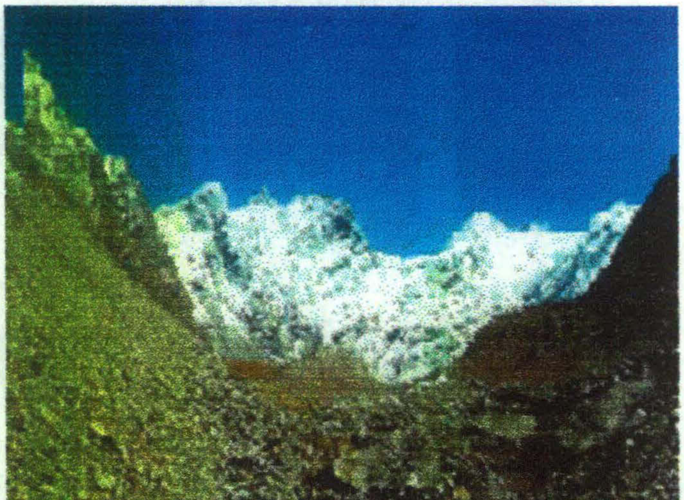
Dedicated to my beloved parents



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Certificate

The research work embodied in this thesis **"Ecohydrological studies of Dokriani glacierised basin, Garhwal Himalaya, Uttaranchal"**, has been carried out in the School of Environmental Sciences, Jawaharlal Nehru University, New Delhi. This work is original and has not been submitted in part or full for any other degree or diploma in any University / Institution.

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Chapter I

INTRODUCTION

1.1 GENERAL

The recent emphasis on sustainable economic development has encouraged thinking in terms of sustainable management of water on a holistic basis, taking into consideration its relationship with other natural resources as well as with other natural and human processes that affect the quality and quantity of water in terms of long-term supply.

As acknowledged by the Earth Summit in Rio (1992) and more recently the World Summit on Sustainable Development (WSSD, 2002), mountains are vital to all life on earth and to the well being of people everywhere. Mountains are indeed the source of many services and benefits upon which the quality of our life depends. Over half of the global population depends on mountain resources. The mountain regions of developing countries alone are home to some 625 million people, representing 10 per cent of the world's population.

To meet the increasing demand of population and industrialization all over the world, continuous development of new sources of water for irrigation, hydropower, domestic and industrial supply is needed. Since, glaciers are important source of water, the study of glaciers in various forms is of vital interest. In context of India, majority of the rivers originating from Himalayas have their upper catchment in the snow-covered areas and flow through steep mountains. The Indus, Ganga and Brahmaputra river system, which receive a substantial amount of melt water from the Himalaya, are considered as the lifeline of the Indian sub-continent. The estimation of the volume of water draining out from the snow and glaciers is needed for assessment and management of Himalayan water resources. The planning of new multipurpose projects on the Himalayan rivers in the country further emphasizes the need for reliable estimate of snow and glacier melt runoff and sediment transport by melt water streams. Therefore, a hydrological investigation of the Himalayan regions where monsoon rain penetrates the high altitude valley glaciers and coincides with glacier runoff is of immense significance.

1.2 EVOLUTION OF GLACIOLOGY IN INDIA

It was Jean Louis Radolphe Agassiz, who proposed the first glacial theory in 1837 in his presidential address to the Swiss Society of Natural Sciences. The observations made by him were published in 1840 in a book titled " Etudes Sur Les Glaciers". In the British India, Geologists and Naturalists took great interest in the glacial theory as proposed by Agassiz and many papers describing the glacial geology and geomorphology were published. E. Madden discovered a glacier in 1847, in Kumaon Himalaya, which he named Pindari glacier. Godwin-Austin brought the glaciers in the Karakoram Mountain to the notice in 1862. The other notable studies on glaciers in the 19th century were done by Batten (1845), Humboldt (1845), Cunninham (1849), Greisbach (1887) and Oldham (1904).

From the beginning of twentieth century the Geological Survey of India (GSI) has been actively involved in the study of glaciers in its various forms. Between 1907 and 1910 it had started monitoring glacier fluctuations in the Himalayan region. Auden, in 1937 published a comprehensive report on the snout of Gangotri glacier, in Garhwal Himalaya, in which he reported that during the Pleistocene period the Gangotri glacier descended at least as far as just below Gangotri town (located 18 km downstream to the present snout location).

First International Geophysical year (1957- 1958) and later International hydrological decade (1965-1974) have motivated the countries sharing the Hindukush Himalaya (India, China, Nepal, Pakistan, Bhutan and Afghanistan) to initiate studies on snow and glaciers. In India the responsibility of studying the glaciers in the Hindukush Himalaya was handed over to the Geological Survey of India and it played a very important role. But none of the glacier was monitored regularly on long-term basis. In 1986, however the Department of Science and Technology, Govt. of India, initiated a national level coordinated scientific programme on Himalayan glaciology. Under this programme Chhota Shigri glacier in Lahaul-Spiti valley, Himachal Pradesh was studied between 1987 and 1990.

The Department of Science and Technology, Govt. of India, have now evolved a long-term research programme for Himalayan glaciers. The main areas covered under the programme are glacier hydrology, mass balance, water quality, sediment transfer, glacial fluctuation and remote sensing.

1.3 GLACIERS AS INDICATORS OF CLIMATE CHANGE

The climate of Himalaya is essentially dominated by the southwest monsoon, which provides most of the precipitation in the eastern and central region during the summer months. The westerlies which predominate during the rest of the year bring snow and rain in the winter and spring period, most significantly in the western part of the mountain system. The Himalayan mountain system blocks the northward advancement of monsoon causing widespread precipitation on the southern side of the Himalaya, making the Tibetan plateau and northern rain shadow area as one of the driest regions of the world. This indicates that the most important source of water in the Western and Central Indian Himalaya comes from the monsoon rainfall, snow and glacier ice-melt. About 75% of the run-off in three major river systems, the Indus, Ganga and Brahmaputra occurs between June and September in response to the snow and glacier ice-melt (Collins and Hasnain, 1995). The water supply to these rivers from glaciers during the melting and lean season is more stable and predictable than that during rainfall.

Glaciers are sensitive to climate change, hence act as indicators of climate change within a time span, growing and wasting in response to changes in temperature and amount of snowfall. Recently many studies have revealed that the glaciers are shrinking at a global scale. Their receding is due to increase in air temperature of about 0.3oC per decade (Brethorton et al., 1990; Folland et al., 1992). IPCC (1996) predicted that up to a quarter of the present mountain glacier mass could disappear by 2050 due to global warming. A decrease of glacier mass of this magnitude presents a serious water resources problem for the millions of people living within the Himalayan region.

The melting of ice and consequent formation of glacial lakes has increased the risk and incidence of landslide and glacier outburst floods in mountainous area. This will have an uncertain effect upon water supply from glacier fed streams and may cause havoc down-stream. According to the United Nations (National Geographic News, May 7, 2002) dozens of lakes in Nepal and Bhutan are overflowing due to melting of glaciers to such extent that they could burst in the next five years and devastate many Himalayan villages. It has been jointly predicted by scientists from the United Nations Environment Programme (UNEP), along with remote sensing experts from International Center for Integrated Mountain Development (ICIMOD), Katmandu, Nepal that in the next half a decade or so the Himalaya could experience intense flooding as mountain lakes overflow with water from melting glaciers and snowfields (National Geographic News, May 7, 2002).

A glacier is a very suitable tool for the measurement of atmospheric conditions. From a study of present day coupling between glaciers and their environment we can retrieve the information about past climates that is stored in glacier and in the morphology of it's surrounding. The optimism however is damped by the fact that the signal from the immediate vicinity may be of a similar magnitude to that from the atmosphere. In extreme cases, the system will undergo irreversible changes since the glacier response is faster than that of morphological or botanical adjustments.

1.4 ECOHYDROLOGY OF HIMALAYAN REGION

The concept of ecohydrology is relatively recent. In India, ecohydrological studies are launched as a scientific pursuit by the last few years. To study ecohydrology of a region full-fledged study involving scientific communities from different disciplines is of vital interest. Water occurs in various forms in ecosystem and interacts with lithosphere and atmosphere. Thus, ecohydrology covers a broad spectrum of subjects, physics of ice/ snow, chemistry of liquid precipitation and snow, hydrology of streams, glaciology and biology etc. Climatic conditions persisting over the Himalayan region regulate the ecohydrology of the north Indian rivers which maintain their flow due to snowmelt during March to May, and glacier melting in May and June when condition prevails over the plains (Bahadur, 1996).

Keeping in view the importance of glaciers as a valuable source of water, the International Hydrological Decade (1965-1974) included major programmes related to glacier hydrology. Valuable information was gathered under this programme, which enabled us to know more about glaciers. In context of India, the glacier contribution to the rivers originating from Himalayas starts in the month of June–July when seasonal snow and ice cover is ablated. This flow continues till October-November depending upon the climatic conditions in that region.

Himalayan ecosystem, by virtue of its recent origin, is a fragile ecosystem. Therefore, the ecohydrology of the region is very sensitive to climate change and environmental pollution. The ecohydrological conditions of the Himalayan Rivers have witnessed tremendous changes in the last two decades due to anthropogenic activities such as tourism, mountaineering, adventurous sports and these may have indirect effects by way of alteration of chemical composition of atmosphere through the buildup of greenhouse gases primarily carbon dioxide, methane and nitrous oxide which have undisputed heat trapping properties.

Glaciers in the Indian Himalaya cover an area of 38,039 km2, broadly divided into three-river basins- Indus, Ganga and Brahmaputra. The Indus basin has the largest number of glaciers 3,538 followed by the Ganga basin with 1,020 glaciers and Brahmaputra basin having 662 glaciers. The glaciers are situated in five states-Jammu and Kashmir, Himachal Pradesh, Uttaranchal, Sikkim and Arunachal Pradesh. Kashmir has the largest concentration with 3,136 glaciers covering 32,000 km2, nearly 13% of the state's territory. The average area of a glacier in the state is 10.24 km2. Various researchers have estimated that about 17% of the Himalaya and 37% of Karakoram are covered by glacier ice. The principal glaciers of the Himalaya are Siachen (72 km), Gangotri (25 km), Zemu (26 km), Milam (19 Km) and Kedarnath (14.5 km).

Vohra (1996) stated that the glaciers are found in all those areas, which attain or exceed the heights necessary for glacier generation. The major clusters of glaciers occur in and around the following ten Himalayan peaks and massifs-Nanga Parbat, Nanda Devi group, the Dhaulagiri Massif, the Everest-Makalu group, the Kanchenjunga, the Kula-Kangri area and Namcha-Barwa.

Although snow and glacier ice has long been the subject of scientific investigation, the vast majority of the studies have been limited to various disciplines in the physical and biological sciences. As a result, very few works permit a full appreciation of snow/ice-covered regions as functional ecosystem. Although snow and ice may cover lesser areas of the earth than non-snow areas at any time, strong feedback mechanism between snow, ice and the atmosphere can influence the whole biosphere. Thus, snow and ice can be considered to play a role in the dynamics of all ecosystems (Groisman and Davies, 1999). This can be well exemplified by the large-scale effects of snow-cover on Eurasia on the global scale. An above normal snow cover in Eurasia and Tibetan plateau will delay or weaken the Indian monsoon giving lower than normal precipitation and also effect climate in the tropical Pacific and North America (Barnett et al., 1989). Therefore, the climate of the Himalayan region is interconnected with the climate of other snow covered regions of the world.

In general, the high mountain systems are very sensitive environments, which offer unique challenges to, and opportunities for global change research. Under UNCED (United Nations Commission on Environment and Development) Agenda 21 entitled 'managing fragile ecosystems-sustainable mountain development' the so-called mountain agenda; special relevance is attached to generating and strengthening the knowledge of ecology and sustainable development of mountain ecosystems and promoting integrated watershed development and alternative livelihood opportunities. South Asian Regional Working Group supported by UNESCO on mountain hydrology (March, 1992) recommended that the scientific studies to understand the snow and ice processes including glacier dynamics and atmospheric processes influencing them in the high mountain environment should be promoted and encouraged in the Hindukush Himalaya.

In general it can be said that the mountain hydrology and water management plays a crucial role as we have to deal with ecosystem in changing moisture and temperature conditions on the ground depending on altitude and location (latitude, longitude, and distance from ocean-the source and snow and ice fields-the sink). Therefore, the study of the Himalayan hydrology and various processes attached to it is of immense significance to the scientific community as a whole. The hydrology and hydrochemistry of the Himalayan glacier melt water plays an important role in maintaining the overall stability of the ecosystem.

1.5 OBJECTIVES OF THE STUDY

The Dokriani glacier, source of Din gad is a small glacier of 5 km length. Din Gad joins river Bhagirathi near Bhukki village. The main objectives of the study were:

- To study the major ion chemistry of Dokriani glacier melt water during the ablation seasons (1999-2001). This involved the determination of major cations (Ca2+, Mg2+, Na+, K+) and anions (HCO3-, SO42-, Cl-).
- To understand the processes of weathering and therefore, to find out the source of solute in the melt water.
- To investigate the diurnal and seasonal variation in discharge and suspended sediment concentration (SSC) and runoff characteristics of the glacier.
- To estimate suspended sediment load transported by Dokriani glacier melt water for the given ablation seasons.
- Collection of meteorological data like rainfall, air and water temperature to find out the overall interaction of meteorological parameters with the glacier basin.
- To study the hydrological system of glacier and hence measurement of discharge using dye- tracer technique.

1.6 SCOPE OF PRESENT STUDY

The study on glacier and ice is of vital importance because most of the Himalayan rivers are snow fed. Water discharge in the snow fed rivers depends on the degree of glaciation i.e., the number of glaciers present and total ice cover in the basin. The information about distribution of glaciers is therefore, a basic requirement for hydrological estimation and water resource management (Vohra 1992). Glaciers are very powerful agents of erosion and contribute a substantial amount of sediments as well as solutes to the river system. Hence, better understanding of hydrological responses of glaciated catchment is necessary for formulation of efficient water resource management programmes. The purpose of this study is to find out the complicated processes operating in the glacial environment, which ultimately influence life in the plains. The results obtained in this study have shown that the water levels sustained by mighty Himalayan rivers are the consequences of the water discharge from the glaciers. Huge sediment load generated by glacial melt water is transported to the northern Indian plains by glacier fed rivers. Study of seasonal and diurnal variations in suspended sediment concentration in the river is useful in planning of construction of dams and reservoirs for irrigation and hydropower generation.

Chapter II

LITERATURE REVIEW

LITERATURE REVIEW

The studies on mountainous ecosystems are of great interest primarily due to the fact that they influence the climate and weather and secondarily on account of their being rich source of water-a major life supporting system on earth. About 80% of fresh water of the planet Earth comes from mountains (Barry, 1992). Altogether half of the global population as well as the wide array of plant and animal life rely on mountain watershed for fresh water. Therefore, it is important that this resource is undisturbed beyond repair.

Himalaya, world's mightiest mountain system is the huge reservoir of fresh water and biological resources. The vegetation cover of the Himalaya shows an altitudinal as well as east to west variation. This variation is due to longitudinal and altitudinal difference in rainfall and temperature. The Himalaya is also prone to tectonic activities like earthquake. Beside earthquakes, natural hazards like landslide, snow avalanches, mudflow and glacial outburst floods offer great challenge in managing the ecohydrology of headwaters (Bahadur, 1996). Regional gradient of moisture, temperature, and vegetation cover plays an important role in the hydrological processes of the region (Hewitt, 1982).

2.1 INVENTORY OF HIMALAYAN GLACIERS

There are nearly 15,000 glaciers in the Himalaya lying between the two syntaxial bends of the Hindukush- Karakoram ranges in the west and Himalaya- Patkai Bhum ranges in the east. It is reported that during Pleistocene period 4.0 x 10^5 km^2 of the Himalaya was covered by glaciers whereas it is only 43,000 km^2 today (Geological Survey of India, 1961). Areal distribution of perennial ice and snow cover in the Indian Himalayan region was compiled from various maps and references by Fujii and Watanbe (1983) as shown in Table 2.1. However the accuracy of estimated areas is limited since only a few regions were covered in the exact mapping. Kaul (1999) gave the inventory of Himalayan glaciers for five drainage basins namely Jhelum and parts of Sutluj in the Indus basin (Table 2.2) and Bhagirathi, Tista and Arunachal Pradesh in the Ganga-Brahmaputra basin (Table 2.3). Each basin catalogues information on total basin area, number of glaciers, glacierised area, percentage of glacierised area, area wise and lengthwise distribution of glaciers and total ice volume. The glaciers in the Himalaya mostly belong to Indus, Ganga and Brahmaputra river system. The size of glaciers varies from less than 1 km to as large as 72 km (Siachin glacier). Glaciers in Himalaya occur mainly in two forms. The large glaciers occupy intermontanne valleys and form valley glaciers, whereas a large number of smaller glaciers occupy cirques at higher altitude, which come under the category of Mountain glaciers (UNESCO, 1970). The large valley glaciers are compound basin types, as these are formed by joining of tributary glaciers with the trunk glacier. A characteristic feature of Himalayan valley glaciers is the unexposed nature of lower ablation zone, on account of being covered by surface moraines. Another conspicuous feature of the valley glaciers is the presence of lateral moraine ridges on the sides of the glacier. The morainic debris of larger valley glaciers extend much downstream of the present snout of the glaciers, which signifies the once much larger spread of the ice cover in the past.

A characteristic feature of Himalayan glacier is that they receive annual accumulation mainly in the summer by monsoonal rainfall. The monsoon precipitation in summer (June-September) constitutes about 80% of annual precipitation. Ageta and Higuchi (1984) named these glaciers, which have more accumulation in summer than winter, as the 'summer accumulation type' and differentiated them from the 'winter-accumulation type' glaciers well known in Europe and North America. On the summer accumulation type glaciers, accumulation and ablation may occur simultaneously in summer. Under such conditions, summer snowfall sometimes changes to rain under warm air temperature condition, and also new snow cover melts away quickly. Consequently, summer air temperature in the Himalaya is an important factor, which controls ablation through albedo variation at the glacier surface.

Table 2.1: Perennial ice cover in the Himalaya

Region	Area (km²)	Total area (km²)	
Indus basin	700		
Jhelum basin	370		
Chenab basin	3820	Punjab Himalaya	6210
Ravi, Beas basin	720		
Sutluj basin	600		
Sutluj basin	5790		
Jamuna basin	340	Kumaon Himalaya	13, 320
Ganga and Kali	7190		
Tista	630	Sikkim Himalaya	630
Bhutan Himalaya	2730		
Northern Assam	2060	Assam Himalaya	5180
Namche Barwa Massif	390		
Karnali basin	460		
Gandak basin	510	Nepal Himalaya	2620
Kosi basin	850		
Tibatan basin	800		
Whole Himalaya			27,960

Source: Fujji and Watanbe, 1983

The growing pressure for greater utilisation of Himalayan waters derives largely from the strong economic interests of the plains. The possibilities of economic transformation, both within and adjacent to the Himalaya, are enormous if only part of the water volume can be stored, or diverted and distributed more uniformly in space and time. Any such processes however must be integrated with an understanding of the regional environmental and social conditions (Bandyopadhyay and Gyawali, 1994). The International conference on Ecohydrology of high mountain areas, held in March 1996 in Kathmandu, Nepal has highlighted regional issues in ecohydrology, such as data collection and information systems, atmospheric, hydrological and ecological interaction, water induced hazards of erosion, sedimentation and landscape processes. The Kathmandu declaration adopted at the end of the conference recommended that collaborative studies of the hydrological and ecological processes be undertaken along altitudinal gradients taking into account the areal distribution of their parameters in mountainous catchments.

Table 2.2: A status of the glacier inventory of Indus Basin

Basin	Numbers of glaciers	Glacierised area (km^2)	Ice volume (km^2)
Jhelum	133	94.0	3.0
Satluj	224	420.0	23.0
Others	3398	33382.0	-
Total	3755	33896.0	26.0

Source: Kaul, 1999

Table 2.3: A status of the glacier inventory of Ganga-Brahmaputra basins

Basin	Number of glaciers	Glacierised area (km^2)	Ice volume (km^2)
Bhagirathi	238	755.0	67.0
Tista	449	706.0	40.0
Brahmaputra (Arunachal Pradesh)	161	223.0	10.0
Others	640	2378.0	-
Total	1488	4062.0	117

Source: Kaul, 1999

2.2 RECESSION OF HIMALAYAN GLACIERS

Himalayan glaciers are in a constant state of recession. Behaviour of transverse glaciers is quite complex than longitudinal glaciers probably due to the fact that these are shorter and flow is perpendicular to the incoming circulation pattern and have steeper gradient (Mayewski and Jeschke, 1979). Retreats of some of the Himalayan glaciers are given in Table 2.4.

Table 2.4: Retreat of few Himalayan glaciers

Glacier	Period of observation	Retreat (m)
Pindari (Uttar Pradesh)	1845-1966	2840
Milam (Uttar Pradesh)	1849-1957	1450
Shaunkulpta (Jammu and Kashmir)	1881-1965	518
Zemu (Sikkim)	1909-1965	44
Gangotri (Uttaranchal)	1935-1975	600
Bara Shigri (Himachal Pradesh)	1892-1945	1100

Source: Upadhyay, 1995

Change in mean atmospheric temperature between 1880 and 1985 indicates an average increase of about 1°C in global temperature during the period of 105 years (Hansen and Lebedeff, 1987). There has been constant warming during the period barring a short span between 1940 and 1965, which was the period of comparative cooling. There were however, significant regional variations like the one during 1880 and 1940 when Peruvian Andes experienced a temperature rise of 3-5°C but cordillera of western Canada during the same period became warmer by 1-2°C only. The relationship between climate variations and glacier mass balance is not simple. In general, the glaciers have shown greater sensitivity to rise in temperature than to increase in rainfall (Oerlemans and Fortuins, 1992).

Constrained by paucity of data on gross temperature rise in the recent past and by the non-availability of the data on ice volume and lateral spread changes, the movements of the glacier termini have been used for interpretation of glacier fluctuation. The records available on these phenomena extending back over 150 years also indicate a general retreat of Himalayan and Trans-Himalayan glaciers since 1850 (Mayewski and Jaschke, 1979).

The coordinated collection of information about glacier began in 1894 with the purpose of clarifying the relationship between glaciers and climate, and improving understanding of Ice Ages. Until about 1950, most of the information collected was related to glacier lengths, particularly in Alps, Scandinavia, Iceland, Canada, Patagonia and Andes. Direct mass balance studies began after Second World War, first in Scandinavia and then elsewhere, many in conjunction with hydroelectric schemes. It was their work that established the link between climate change and glacier fluctuations. The need for a worldwide inventory of perennial snow and ice masses was first considered during the International Hydrological Decade operated by UNESCO during 1965-1974. The reaction of a glacier to small climatic variations can be described by a combination of energy and mass budget. The behaviour of the equilibrium line is predictable from accumulation, radiation budget and air temperature and their vertical gradients. Climatic trends are clearly reflected in mass balance and temperature changes in glaciers and permafrost. It is for this reason that perennial land-ice bodies are key parameters for climate system monitoring (Haeberli, 1990; Haeberli and Beniston, 1998).

2.3 GLACIAL HYDROLOGICAL SYSTEM OF A MOUNTAIN GLACIER

The hydrology of glacierised regions is thermally controlled. Runoff results from interaction of precipitation with environmental thermodynamic characteristics. Variations in energy availability lead to fluctuations in melting of snow and ice and the production of melt water. Because of thermal threshold snow and ice masses are prevented from entering the liquid phase until the critical melting temperature is attained. Seasonal variations in the form of precipitation from winter snowfall to summer rain, and of energy supply usually peaking to a summer maximum, produce strong seasonal periodicity of hydrological event which influences quantity, quality and timing of drainage (Young, 1985).

The water moves through the glacial system in several ways. The difficulties in conceptualising complete basin hydrology lie in the fact that there are seasonal dimensions involved (Young, 1982). The internal networking system of a mountain glacier consists of vertical pipes, which in literary parlance are known as moulins, connecting with basal conduits joining to one or several major tunnels leading to portals.

In early spring and winter, conduits in ice close causing water to become stored by being sealed off in small cavities and channels, especially at the base of the glacier (Tangborn et al., 1975). Pressure exerted by snow cover during winter may also have a tendency to close basal passageways. During late spring when melting resumes, water pressure slowly raises. As the summer advances internal drainage system of the glacier changes into linked cavity system. Variations in atmospheric and cloud conditions cause glacier fluctuations. The change in climate of the area is reflected in glacier mass balance. The mass balance is calculated as the sum of accumulation (amount of snow and ice added to a glacier, taken as positive) and ablation (amount of snow and ice lost from a glacier, taken as negative). Accumulation is the result of solid precipitation and from sublimation (condensation) of water vapour, both of which are input directly from the atmosphere to the glacier surface. Avalanches, snow drifting and freezing of melt water and rain inside the glacier can contribute to accumulation indirectly. Accumulation and ablation (Fig. 2.1) have annual cycles dependent on seasonal climates and the cumulative results of annual mass balance cause glacier variations (Nakawo and Hayakawa, 1998). Since the glacier observations started in USA and Europe, it was originally thought that glaciers accumulate in winter and ablation starts in summer only. Recent studies by Ageta and Higuchi (1984)

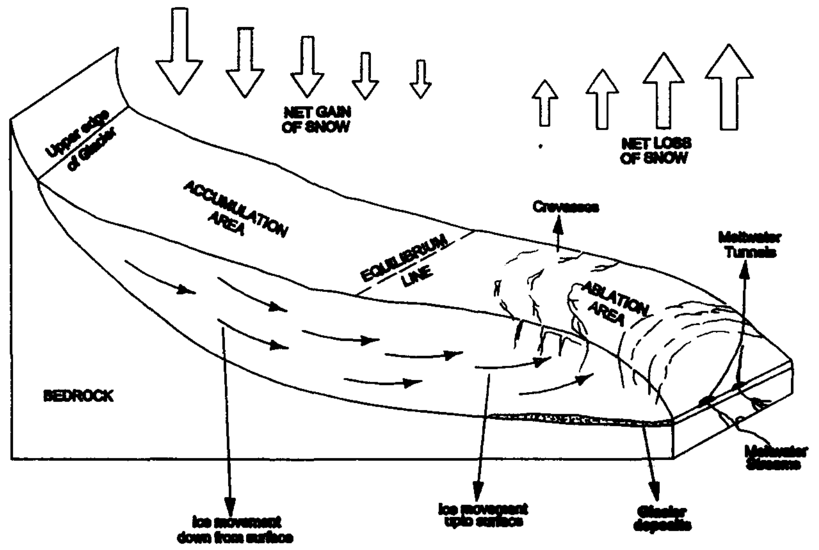


Fig. 2.1: A model of glacier showing the relationship between accumulation and ablation area

have shown that in Asia, the major part of both annual accumulation and ablation occurs simultaneously in summer. For example, in the Himalaya and southern part of Tibetan plateau, summer precipitation results in snowfall at high altitudes.

In high mountain areas, over an annual discharge cycle, specific runoff is higher than in surrounding plains because of greater precipitation inputs and reduced evaporation. With increasing elevation of basins, specific runoff is usually enlarged. However, the distinctive characteristics of high mountain runoff relate to the timing of flows. Because some of the precipitation accumulates in snow pack in winter, at temperature below freezing point, much runoff is delayed from the time of precipitation until later in the year. Flows of rivers and streams in mountain are therefore, concentrated in spring and summer months, when water is released by melting of snow and glacier ice. In contrast winter discharges are very low or negligible, according to the duration of the temperature below freezing point. Mountain runoff therefore reflects change in heat energy available for melting.

The seasonal variations of runoff from a mountain glacier basin bear little relation to that of precipitation. Essentially a long lag exists between the accumulation of precipitation in winter and its release from the storage during summer in both nival and glacial catchment area. On a daily basis, relationship between precipitation and runoff are complex and depend on the form of input and on conditions at the surface. A characteristic feature of glacierised mountain rivers during the melting season is the pronounced diurnal variations of discharge. Diurnal variations in the supply of energy available for melting snow and ice lead to a rhythmic diurnal flow regime.

2.4 SOLUTE ACQUISITION PROCESSES IN MELTWATER

The runoff from the glacierised valleys in the Himalayan region is contributed by snow/ice melt and monsoonal rainfall, resulting in discharge peak in July/August. However, the dense cloud cover during the southwest monsoon between July and August over the Garhwal Himalaya cuts off the radiation and hence the melt from the glacier ice is reduced (Collins and Hasnain, 1995; Hasnain et al., 2001). The potential of solute acquisition by melt water in the subglacial environment is several times higher than in other glacial environments due to (1) the slow transit time of water within the subglacial system (Tranter and Raiswell, 1991; Trainter et al., 1986, 1993; Brown et al., 1993; Collins, 1995; Brown et al., 1996). (2) the availability of large amount of freshly comminuted rock flour (3) the availability of reactive minerals, such as carbonates and sulphides in the fresh rock flour, which provides additional protons for chemical weathering (Tranter et al.,1993; Brown et al., 1996).The chemical composition of meltwater demonstrate high rates of chemical weathering in subglacial environment (Reynold and Johnson,1972; Collins, 1979; Raiswell,1984; Sharp et al., 1995, Brown et al., 1996). The two major anions, HCO_3^- and SO_4^{2-} in the meltwater are mainly derived from the dissolution of atmospheric carbon dioxide and carbonates, and oxidation of sulphides (Souchez and Lemmens, 1987). Dissociation of CO_2 and Sulphide oxidation are the two main reactions that provide the bulk of protons to weather carbonates, silicates and aluminosilicates in the drainage basin. The anionic content of meltwater therefore, reflects the acidic sources used in the chemical weathering of bedrock minerals. The relative proportions of various ions in solution depend on their relative abundance in the bedrock and their solubility (Raiswell, 1984; Trainter et at, 1993). According to Brown et al., 1996 the ratio of HCO_3^- to ($HCO_3^- + SO_4^{2-}$), referred to as the C-ratio, has a value of 1.0 when carbonation reactions involving atmospheric CO_2 dominates and value of 0.5 when coupled reaction involving the weathering of carbonates by protons derived from sulphide oxidation dominate according to the following reactions:

$CaCO_3\,(s) + CO_2\,(aq) + H_2O\,(aq) = Ca^{2+}\,(aq) + HCO_3^-\,(aq)$

$CaAl_2Si_2O_8\,(s) + 2CO_2\,(aq) + 2H_2O\,(aq) = Ca^{2+}\,(aq) + 2HCO_3^- + H_2Al_2Si_2O_8\,(s)$

(Ca- Feldspar) (Partially weathered Feldspar)

$4FeS_2\,(s) + 16CaCO_3\,(s) + 15O_2\,(aq) + 14H_2O\,(aq) = 16Ca_2^+\,(aq) + 16HCO_3^-(aq)$

(Pyrite) (Calcite) $+ SO_4^{2-}\,(aq) + 4Fe(OH)_3\,(s)$

Therefore, the composition of rock and their ion exchange capacities influence both the rate of weathering and ion supply to runoff and percolating water. Four general processes of weathering are Solution, Oxidation- reduction, the action of H^+ ions and the formation of complexes (Gorham, 1961)

Weathering of the rocks is mainly performed by the action of H^+ ion, which derives from the dissociation of carbonic acid on minerals in the rock. Solution is important in sedimentary deposits rich in soluble salts. Oxidation-reduction process primarily affects iron, manganese, sulphur, nitrogen, phosphorus and carbon compound. Certain soluble organic molecules can chelate or complex ions by bonding, thereby preventing these ions from reacting with others.

Open and closed system solute acquisition

The meltwater is believed to be evolved chemically in the open system, when the atmospheric CO_2 in gas phase is in equilibrium with the amount of dissolved carbon dioxide in the liquid phase. The system is closed when this is not the case. Open and closed system weathering regimes are kinetic phenomena and depend on the rate at which CO_2 diffuses into or out of solution relative to the rate of other chemical weathering reactions (Raiswell, 1984; Raiswell and Thomas, 1984; Thomas and Raiswell, 1984). Schematic representation showing chemical evolution of meltwater routing through open and closed system is given in Fig. 2.2.

Low p (CO_2) system: In this system the rate of weathering is greater than the rate of hydrogen ion supply. The increase in pH induces CO_2 diffusion into solution, as the solution could hold additional dissolved CO_2 when large quantities of englacial flow mix with sediment laden delayed flow at the height of the ablation season (Sharp, 1991). Under these circumstances, the rate of proton consumption is greater than the rate of gaseous diffusion of CO_2 into solution

High p (CO_2) system: This may arise in three types of scenario. First, input of protons to the drainage system may occur, so as to give a short lived reduction in pH, when acidic snowmelt mixes with a subglacial water body. This scenario is transient in

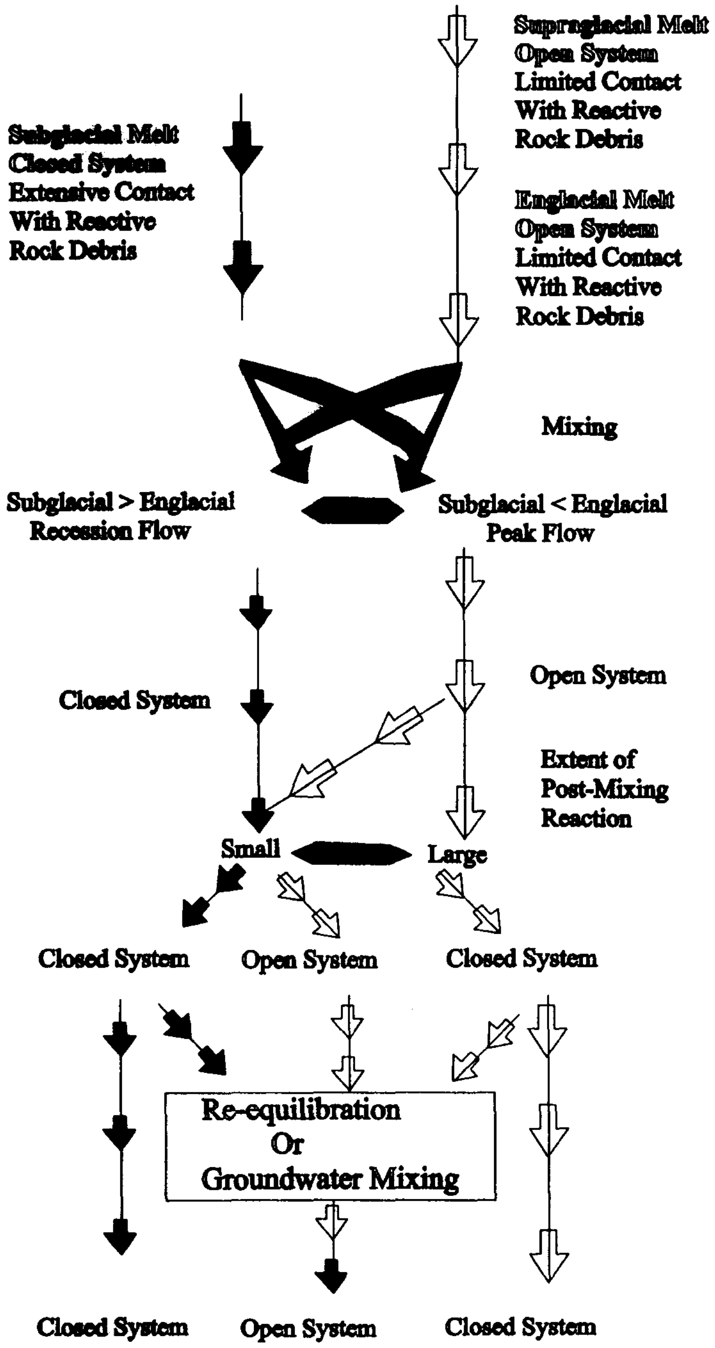


Fig11 Chemical Evolution of Meltwaters routing Through Open and Closed System (Raiswell, 1984)

most subglacial environment, since rock flour has a great capacity for absorbing protons. Secondly, the freezing of water body may result in an increase in p $(CO_2)(aq)$, particularly in water filled cavities or channels when there is only limited opportunity for the solution to degas. Water of delayed flow contains both high concentration of HCO_3^- and SO_4^{2-}.The mass fraction of sulphate is defined as the ratio of SO_4^{2-} to the sum of SO_4^{2-} and HCO_3^-, where concentrations are in units of equivalent. This suggests that delayed flow, which dominates at lower discharge, contains a higher mass fraction of SO_4^{2-} than quick flow, which further suggested that the atmospheric CO_2 of bulk meltwater increases as mass fraction of SO_4^{2-} increases.

The combination of high concentration of Ca^{2+}, HCO_3^- and SO_4^{2-} in the delayed flow in conjunction with elevated atmospheric CO_2 values tends to suggest that the processes of sulphide oxidation and carbonates dissolution are dominant controls on the composition of delayed flow.

$$4FeS_2\,(s) + 16CaCO_3\,(s) + 15O_2\,(aq) + 14\,H_2O\,(aq) = 16\,Ca^{2+}\,(aq) + 16\,HCO_3^-\,(aq) + 8SO_4^{2-}\,(aq) + 4\,Fe\,(OH)_3\,(s)$$

Thus, the solute acquisition in melt water stresses that dissolution and gas diffusion kinetics is important control on the composition of the two major components and their post-mixing chemical evolution. These reactions kinetics are dependent on the residence time of waters within the channel and distributed system, the suspended sediment concentrations (SSC) and the access of atmospheric gas supply. The factors constantly change during the ablation season as the glacial drainage system evolves.

2.5 CHEMICAL COMPOSITION OF MELTWATER

There are diverse opinions regarding the factors, which control the water composition. Gorham (1961) and Gibbs (1967), described climate, geology, topography, biota and time as principal environmental factors, which interact to determine the concentration and composition of atmospheric precipitation, soil solution and surface water bodies.

R.J. Gibbs (1970), proposed atmospheric precipitation, rocks dominance and the evapocrystallisation processes as major factors controlling the composition of dissolved salts of meltwater. The concentration of hydrogen ions in the water plays an important role in the chemical weathering of minerals (Lemmens and Roger, 1978; Raiswell, 1984). Beside the above-mentioned factors, water flow rate and rock mineralogy influence the chemical weathering to a greater extent (Raiswell, 1984).

Geochemical studies of (Rainwater and Guy, 1961) have proved that chemical weathering substantially contributes to the denudation with the glacier environment. The focus of geochemical studies in the glaciated region has been two folds: the first has to establish removal rate of the major cation and anion in glacier meltwater to define the glacial geochemical denudation rates. The second study concentrates on the relationship between solute and suspension activity (Souchez and Lorrain, 1975, 1978; Lemmens and Roger 1978; Collins, 1979). According to Meyback (1981) Ca^{2+} and HCO_3^{2-}dominate more than 97% of the world fresh water. Raiswell (1984) has plotted various parameters like pH, sum of cations and cation composition. Ca^{2+} is the dominant cation in approximately 90% of the meltwater and often comprises more than 70% of total cation equivalent. Among anions HCO_3^- and SO_4^{2-} are the most dominant ionic species in the meltwater.

The chemical analysis of glacial meltwater collected at discharge site near the glacial terminus shows the richness in dissolved chemical species, which is indicative of effective hydrochemical reactions within glacial environment. Dissolved and suspended sediment loads in glacial meltwater are the by-products of chemical and physical denudation. Regarding the chemical composition of material transported in the solution Meyback (1981) says that 80% of the dissolved load in the fresh water system is generally made up of just four components (HCO_3^-, SO_4^{2-}, Ca^{2+} and SiO_2).

Chemical composition of meltwater does not alter much from the frontal part of glaciers to further downstream. Reynolds (1972) compared the water flowing out of

Scree cones at the base of Le-Conte Mountain with the Cascade river water 8.3 miles downstream from the outflow of south Cascade lake. He found that the essential character of water was fixed by the time they leave the alpine watershed and little further change occurs during miles of transit downstream. The chemical characteristics of meltwater, particularly Na^+ and K^+ does not change much even after one km of distance from the glacier portal (Lemmens and Roger, 1978).

Dye tracer experiments carried out at the Haut Glacier d' Arolla, Switzerland by Brown et al. (1994) indicated that the subglacial drainage system contains two principal components, a distributed system in which flow velocities are of the order of 0.05 ms^{1-}, and a channelised system in which flow velocities are in the range 0.5- 1.0 ms^{1-} . During the melt season the channelised system expands headwards at the expense of the distributed system, so that by the end of the season it occupies the lowermost 3.0-3.5 km of the 4.0 km long glacier. Headwards growth from the subglacial drainage channel closely follows the up-glacier retreat of the transient summer snowline on the glacier surface. The drainage configuration suggests that a two-component model should adequately describe the subglacial transport of meltwaters.

Subglacial water composition is largely controlled by dissolution of carbonates and gypsum and by the weathering of aluminosilicates, as in natural water in general (Stumm and Morgan, 1981; Morel and Hering, 1993). According to Raiswell (1984), oxidation of pyrite could release protons, which might in turn react with other minerals. Each of these processes will have an individual rate of reaction. Freshly abraded, finely divided products of glacial erosion will react readily with meltwaters. Small quantities of meltwater will acquire solute by percolating slowly through stored subglacial sediment. Considerable, if temporally variable, concentrations on comminuted reactants are derived from channel margins along the entire length of basal hydrological pathways. These become suspended in meltwaters flowing through the network of interlinked subglacial cavities and conduits.

About anions particularly Cl^- and NO_3^-, it is assumed that they are derived mainly from the dissolution of sea salt aerosols (Souchez and Lemmens, 1987). The SO_4^{2-} is mainly derived from the oxidation of sulphides in powdered rock (Tranter and Raiswell, 1991). The two major anions in Alpine glacier meltwaters are HCO_3^- and SO_4^{2-} (Souchez and Lemmens, 1987), because the dissociation of atmospheric CO_2 and the oxidation of sulphides provide the bulk of the protons used to weather carbonates, silicates and aluminosilacate minerals on glacier floor. Hence the supply of atmospheric CO_2 and O_2 to meltwater is a fundamental control on the rate and extent of chemical weathering in glacial meltwaters (Tranter et al., 1993).

2.6 FACTORS CONTROLLING SUSPENDED SEDIMENT TRANSPORT IN HIMALAYAN GLACIER MELTWATERS

Suspended sediment generated by glacier erosion is highest in the Himalayan as compared to other region of the world (Hasnain and Thayyen, 1999). This may be due to high altitude, steep slope, active monsoonal rain as well as recent age of the Himalaya. The ongoing interactions of Indian and Eurasian plates maintain uplift, and high elevation ensures high level of precipitation and large glaciers. Steep, unstable slopes maintain sediment supply to the rivers of the subcontinent (Collins and Hasnain, 1994).

The suspended sediment in glacial meltwater is by-product of mechanical erosion. The subglacial and englacial channels are closed on all sides, and water in them will be under pressure. As a result of which water flow will always be high, which causes abrasion in the underlying bedrock and lot of sediment is generated in the suspension. The amount of suspended sediment in meltwater dependent on the nature and types of rock eroded, glacial abrasion and the rate of glacier melting. The discharge and amount of sediment varies from year to year depending on variable rates of supply of total sediment to the stream network, different source areas, and routing of sediment through the stream network (Gurnell, 1982). When the flow of water is more, it flushes the ions released into water and prevent building up of ions, thus promoting dissolution of material. According to Collins (1979 b), suspended sediment is an important source of solutes in water draining from active glacier. Major cations may also be transported as sorbed ions on the surface of suspended sediment particles.

The suspended sediment in glacial meltwater is more than non-glacial fed river. Embleton and King (1975) have observed a five-fold difference in sediment yield between the glacierised Hoffelsjokull river in Iceland and a nearby non glacier fed river. Harbor and Warburton (1993) demonstrated that the rates of erosion are higher for glaciated areas than non-glaciated areas. The presence of unsorted deposits of sediment found in the area is an indication of potential of glaciers in the production of sediment. A number of studies (Ferguson, 1984; Warburton, 1990 a, 1990 b) have demonstrated that specific sediment yield may increase downstream due to remobilisation of sediment pushed by active glaciers. A survey of sediment yield from 1358 drainage basis with an area ranging from 350 to 100,000 km2 (Jansson, 1988) found that within particular climate zones where glaciers are active, sediment yield tends to be higher. Beside abrasion, plucking, quarrying, crushing and shearing are the physical weathering processes, which are responsible for release of sediment in glacial meltwater.

Rates of sediment erosion in the Himalaya are among the highest in the world. Most of the sediment originates in the glacierised areas and begins its journey to the rivers mixed and pushed by glacier meltwaters. The suspended sediment transport in the proglacial streams in the Himalayan uplands is controlled by glacial area, glacier activity (retreating), monsoon rainfall, and changing glacial drainage system (Hasnain, 1996).

2.7 RELATIONSHIP BETWEEN DISCHARGE AND SUSPENDED SEDIMENT CONCENTRATION

Diurnal variations in suspended sediment concentration of meltwater are a well-established fact (Ostrem, et al., 1967; Ostrem, 1975; Collins, 1979 a; Gurnell, 1982; Hagen et al., 1983). Detailed investigations on the suspended sediment delivery by meltwater streams have revealed that suspended sediment concentrations in meltwater increase with discharge, but the peak in suspended sediment load occurs before the peaking of the discharge.

Several workers, Borland (1961), Ostrem (1975) and Collins (1979 a) have implied rating curves to describe and estimate the level of suspended sediment transport in proglacial streams. Since the flow of water in a stream transports the sediments it follows logically to anticipate a relationship between the suspended sediment concentration and the discharge of the stream. It has been observed that the supply of sediments does not impose a constraint on the suspended sediment concentration discharge relationship. However, the results obtained from the rating curves to estimate the suspended sediment transport from glacial meltwater stream are very period specific. Ostrem (1975) noted that it was possible to establish separate curves for some sub-periods but it would be valid for very short periods only and would not be valid for the corresponding period in a following year.

Sediment transport in the glacial meltwater stream occurs throughout the year due to glacial erosion processes and the availability of sediment at the glacier portal in a period of time will be supply related. It depends on how much area of unworked glacier sole becomes integrated with flow and how much sediment is held there. The other controlling factors are the thickness and debris content of basal layer, nature of bedrock, presence or absence of unconsolidated, deforming sub-sole. According to Collins (1989), the bulk of sediment delivery probably results from glacier sliding by bringing basal ice and deforming basal sediment from up-glacier in contact with flowing meltwaters or relocating conduits incised upwards into ice on the areas. A dense network of small conduits arranged at an angle to the direction of glacier flow would be expected to gather more sediment than a few large conduits with alignment parallel with flow. Development of conduit system in this way would explain the decline in sediment flux with progression of ablation season.

The important factors, which control discharge are the heat fluxes and surface energy balance. Precipitation (solid or liquid) generally has a negative influence on the glacier runoff because the incoming solar radiation is reduced due to cloud cover and the new snow has a high albedo. Variations in glacier runoff follow approximately the reverse pattern of a rain-dominated runoff regime. As a result, it is possible to observe a compensation effect in mountain river basins where the upper parts of the basin experience a meltwater runoff regime (nival and glacier regime) and at the same time lower parts of the basins runoff is dominated by rainfall. In glaciated areas, much of the precipitation fall in solid form throughout the year, so that it contributes to mass storage rather than directly to runoff. The amount of precipitation in the form of snow and ice has an inverse effect on the amount of runoff. Precipitation in the form of snow is highly reflective, as result of which it melts more slowly. Thus greater the precipitation in the form of snow, the longer the glacier is covered by a highly reflective material, and the less the runoff.

2.8 DISSOLVED LOAD – DISCHARGE RELATIONSHIP

Available literature (Rainwater and Guy, 1961; Lemmens and Rogers, 1978; Collins, 1979, 1979 a) suggests that there is an inverse relationship between dissolved load and discharge. This relationship between discharge and dissolved load in glacial meltwaters is sometimes defined by a straight line on a bilogarithmic graph. An inverse relationship of the type $C = kQ^{-n}$ is exhibited, where C is the concentration of dissolved substances, Q the discharge, k a constant and n an exponent having, for example, a value of 0.6 in the Chamberlain glacier in Alaska (Rainwater and Guy, 1961). In non-glacierised catchments this relationship is usually described by the model $c = aQ^{-b}$, where c is concentration of dissolved solids and Q discharge (Hem, 1970). In the case of the Tsidjiore Nouve glacier meltstream, equations have been obtained for the concentration of Na^+, K^+, Ca^{2+} and Mg^{2+} in the samples collected in June, July and August. If discharge is expressed in m^3s^{-1} and concentration in μeq/l, then:

For Na, $C = 11.22\ Q^{-0.59}$

For K $C = 10.47\ Q^{-0.37}$

For Ca $C = 263.02\ Q^{-0.54}$

For Mg $C = 27.54\ Q^{-0.72}$

Thus, higher discharges were characterized by a lower concentration of the four cations. The correlation coefficients were significant at a confidence level of 0.999 and were -0.83 for Na, -0.70 for K, and 0.95 for Ca and Mg respectively (Lemmens and Roger, 1978; Lemmens, 1978). The concentration range is not connected with the suspended load. Indeed, variations of the concentration per litre of cations absorbed on suspended particles, obtained by multiplying the concentration per gram by the weight of suspended sediment per litre of stream water, were of an order of magnitude less than those for the corresponding dissolved cations expressed in the same units (Lemmens and Roger, 1978). Fluctuations of suspended load cannot therefore, explain variations in dissolved cations. Collins (1979, 1979 a) established the relationship between concentration of dissolved cations and discharge by hydrological mixing model of two waters from two different sources. A dilute surface meltwater, which flows rapidly with little alteration through englacial channels and solute rich water flowing more slowly through the subglacial channels. The results obtained showed an inverse relationship between dissolved load and discharge.

The linear relationship, on a bilogarithmic graph between discharge and dissolved load is not observed for all Alpine meltwater streams studied. Indeed Collins (1979b) while studying the chemical composition of water emerging from the snout of the Gornergletscher, pointed out a great range of ionic concentration associated with a given discharge and showed clockwise hysteresis loops of conductivity and discharge on diurnal time scale.

The use of dye tracer experiments to determine transit times of meltwater from moulins to portal and the use of these transit times to characterise diurnal variation in the length of period of contact between suspended sediment and meltwater beneath the glacier also indicated the relationship between the dissolved solid and discharge. This study provides an indication of diurnal variation of solute concentration that parcels of meltwater draining from the moulins in the lower ablation zone would exhibit on reaching the portal of a glacier.

According to Sharp et al. (1995) the efficacy of chemical weathering in glaciated catchment is attributed to (1) high flushing rates, which ensure that the dilute meltwaters do no reach chemical equilibrium with available sediment and the reaction rates remain high (2) turbulent meltwaters, which transport large amount of fine, freshly ground, chemically reactive rock flour (3) high suspended sediment concentration, which increases with meltwater discharge, thus increasing the flux of reaction sites and (4) the low buffering capacity of dilute meltwaters. When such water comes into contact with large amounts of reactive material, available protons are consumed more rapidly than they can be replaced by diffusion of CO_2 into solution, causing the pH to rise, p (CO_2) to drop, and CO_2 to diffuse into solution.

The link between discharge and CO_2 drawdown suggests a potentially important role for glacially driven chemical weathering in carbon cycling over glacial- interglacial time scale.

2.9 DIURNAL AND SEASONAL VARIATIONS IN DISSOLVED SOLIDS AND SUSPENDED SEDIMENT

Some studies (Lemmens and Roger, 1978; Collins, 1979 a, 1979 b, 1983; Rainwater and Guy, 1961; Fountain, 1992) on hydrochemical characteristics of meltwaters draining from temperate glaciers showed that the concentration of dissolved solids varies continuously with discharge. With increasing discharge the contacts surface between fine bottom sediments and water is less extensive so that a lower concentration in solutes is reached (Lemmens and Roger, 1978). Rhythmic diurnal variations in solute concentration with sharp decrease and less recovery in electrical conductivity values were found at Gornera, Switzerland (Collins, 1979 b, 1983). In the same study it was also observed that there exists an inverse relationship between discharge and dissolved solid concentration. A two-component sub-division of meltwater coming out of glacier was given by Rainwater and Guy (1961), to explain diurnal variations of solute and discharge. It is said that the slow moving water in subglacial system is chemically enriched because of contact with sediment for longer duration. However the supra-glacial component which gains prominence every morning with the restoration of surface ablation, is fast moving and dilute. Because of changes in the surface ablation in response to change of meteorological parameters, volume of supraglacial meltwater varies greatly. The mixing of these two components causes variable dilution of solutes in meltwater with changes in discharge.

Diurnal variations in the concentration of dissolved solids in the meltwaters draining from Gornergletsher glacier, Switzerland were explained by Collins (1979 b), using the two component division of the total flow. However diurnal variations in solute concentration have been explained in terms of quick flow and delayed flow. Quick flow waters are derived largely from ice-melt and pass through a channelised hydrological system quickly (Sharp, 1991; Browns et al., 1994). Conversely delayed flow waters are largely derived from snow-melt and move slowly through a distributed hydrological system e.g. linked water filled cavities (Walder, 1986; Walder and Fowler, 1994). Delayed flow waters are solute rich and exhibit high p (CO_2) characteristics. The slow transit of these waters through a distributed drainage system and predominance of relatively rapid reaction in this environment maximises solute acquisition. Quick flow waters are dilute both because of its rapid transit through ice-walled conduits and open channels, and also because the weathering reactions are fuelled by relatively slow gaseous diffusion of CO_2 into the solution. As a consequence quick flow water usually bears a low or open system p (CO_2) signature (Tranter et al., 1993). Phase difference in the peak discharge and concentration is found in several studies (Collins 1979 b; Fountain, 1992). Fountain (1992) from his studies of meltwater draining from south Cascade glacier Washington, U.S.A has inferred that the phase difference in the discharge and cationic concentration is due to two mechanisms:

1. A monoclinal wave like rising limb of diurnal discharge propagates at a speed faster than the flow of speed of water, because the cations or sediment concentration is carried along at the water speed rather than at the wave speed. The concentration would lag behind discharge.
2. The presence of pools along the flow path quickly transmits and increases in the flow but the solutes or sediments mix in the pool and delay their passage. The residence time of water in an instantaneously mixed pool is the pool volume divided by the water discharge. If many pools exit in a subglacial channel the arrival time of peak concentration would significantly lag peak discharge.

Chapter III

AREA OF STUDY

3.1 DESCRIPTION OF THE GLACIER BASIN

The Dokriani glacier in the Bhagirathi-Ganga basin of Garhwal Himalaya is situated in the Uttarkashi district of Uttaranchal. It extends from latitude 30° 50' N to 30° 52' N and longitude 78° 47' E to 78° 50' E. The location of the Dokriani glacier in glaciated region of the Ganga headwater is shown in Fig. 3.1. The total length of the glacier is 5 km. It originates from Draupadi ka Danda (5716m) and flows in a NNW direction for 2 km and then turns towards WWN direction and flows another 3 km. The stream emerging at the glacial portal is known as Din Gad and it joins with the Bhagirathi River near Bhukki. A view of the Dokriani glacier with its snout visible is shown in Plate 3.1(a) and (b). The total area of the glacial catchment is 10 km^2 of which the glacierised area is 6 km^2 and the non-glacierised area covers the remaining 4 km^2. The average rainfall in the Garhwal Himalaya is between 1000 and 2500mm, of which 80% falls during the monsoon period (July-August-September).

3.2 APPROACH AND ACCESSIBILITY

There is approximately 500-km road distance between Delhi and road head (Bhukki), a small village about 50 km north to Uttarkashi. Bus route from Delhi to Bhukki connects the stations like Haridwar, Rishikesh, Chamba, Tehri and Uttarakashi. A bridge over Bhagirathi River is used for crossing the river. After crossing Bhagirathi river, one has to move eastward to reach the glacier. To reach the glacier snout one has to trek about 25 km from the road head. The trek starts from Bhukki village and passes through thick and dense forest cover. In general one has to make one or two nights halt in between to reach the glacier base camp situated at 3700m. Din Gad valley has dense forest cover compared to other parts of the region as shown in Plate 3.2(a). The tree line ends at about 3600m. From there onwards, open area starts and vegetation is bushy type Plate 3.2(b). Thus almost all trekking is made through the dense forest. The base camp was established near the snout of the glacier (Plate 3.3). Tent accommodation was used for all the years of study. All the activities were monitored from the base camp, except when 24 hrs samplings were carried out, for which temporary accommodation with an alpine tent was made near the gauging station to record stage reading manually.

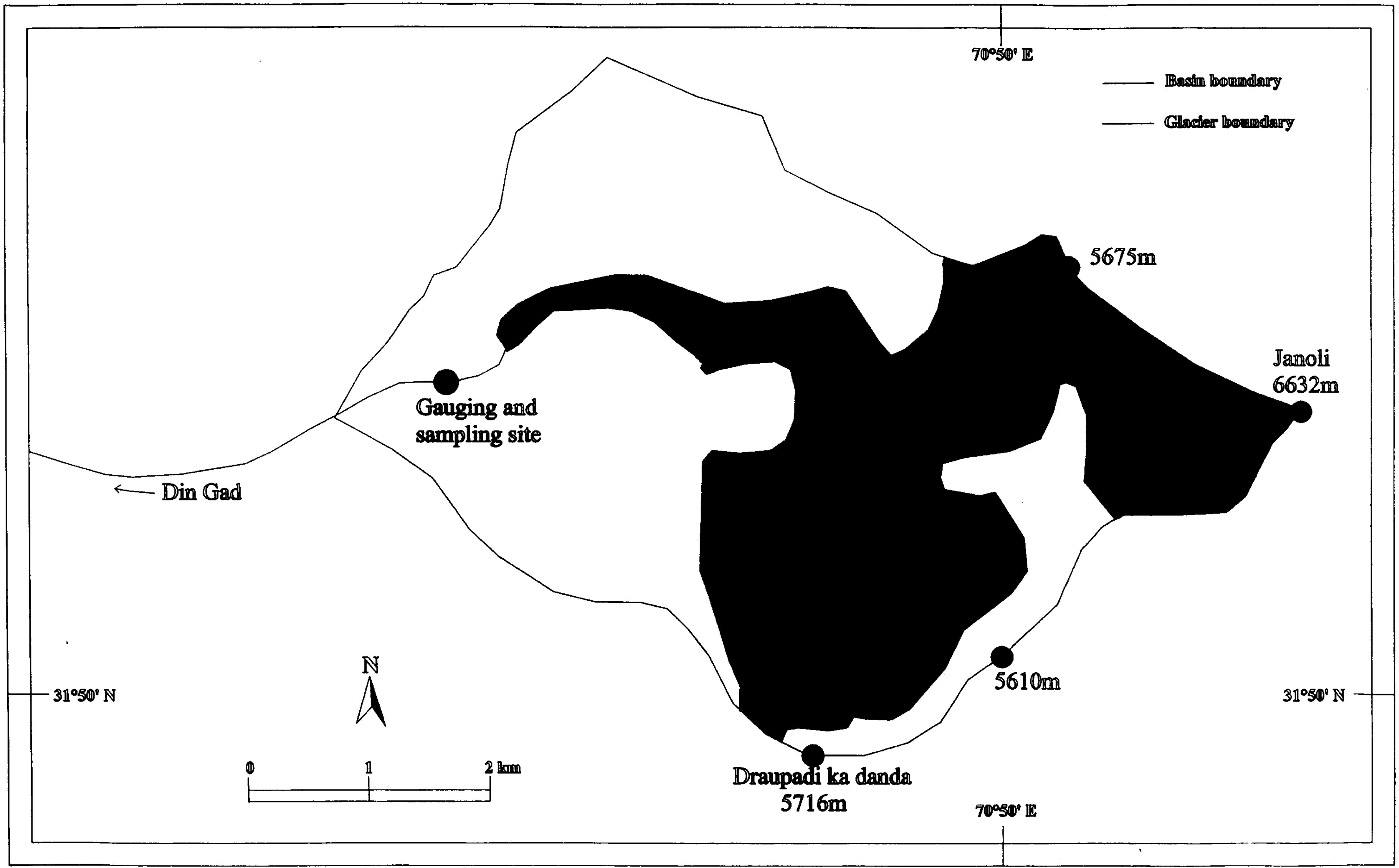


Fig 3.1: Map of Dokriani Glacier Basin

Plate 3.1(a): Synoptic view of Dokriani glacier

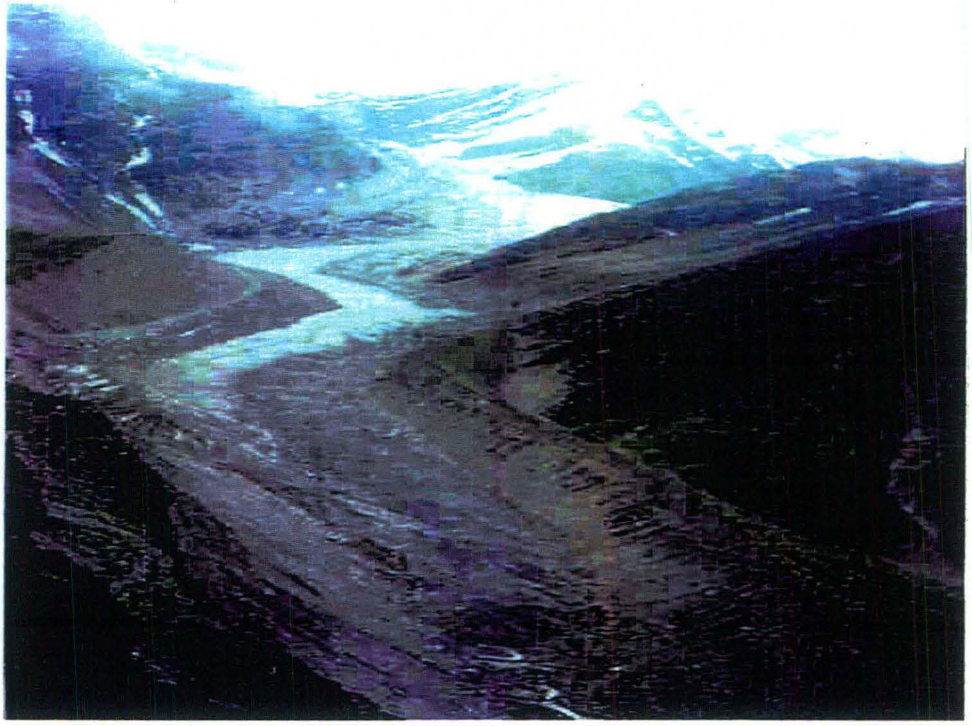


Plate 3.1(b): Dokriani glacier with visible snout and emergence of Proglacial stream

Plate3.2 (a): Dense vegetation cover in the middle of Din Gad valley

Plate 3.2 (b): Sparse vegetation in the upper Din Gad valley

Plate 3.3: Dokriani glacier base camp

3.3 GLACIER SNOUT

Snout of the Dokriani glacier is located at an altitude of about 3900m. The entire snout of glacier ends in a prominent ice cliff and covered by huge boulders and debris. Din Gad emerges from the snout of the glacier. The gauging station has been made about 600m down stream from the glacier portal.

3.4 CREVASSES

Crevasses are cracks or fissures on the surface of the glacier formed by shear stresses set up by differential movement in the ice. In accumulation areas with gentle surface slopes, the ice surface tends to be fairly uniform. When the ice begins to move downslope in the valley the drag of the valley-sides creates shear stresses that produce cracks or crevasses. Many crevasses are found on the Dokriani glacier in the ablation area, which are longitudinal, transverse as well as intermediate type (Plate 3.4).

3.5 MORAINES

Dokriani glacier is covered with extensive lateral and terminal moraines (Plate 3.5). The two lateral moraines i.e. left and right moraines culminate downstream to form end moraine or terminal moraine. These moraines are comprised of debris falling on the surface of the ice by frost weathering, falling boulders, rockslides, avalanches and other types of mass movements. The morainic material is a mixture of angular blocks and boulders and finely- ground rock flour. A large portion of debris is coarse and angular and derived from the rock fragments that fall on to the glacier after frost shattering of the exposed slopes along the sides of the glacier. Due to retreat of the glacier portal enormous heaps of terminal and recessional moraines are left behind. The remnants of terminal moraines can be observed upto Gujjar hut that is about 4 km downstream of snout.

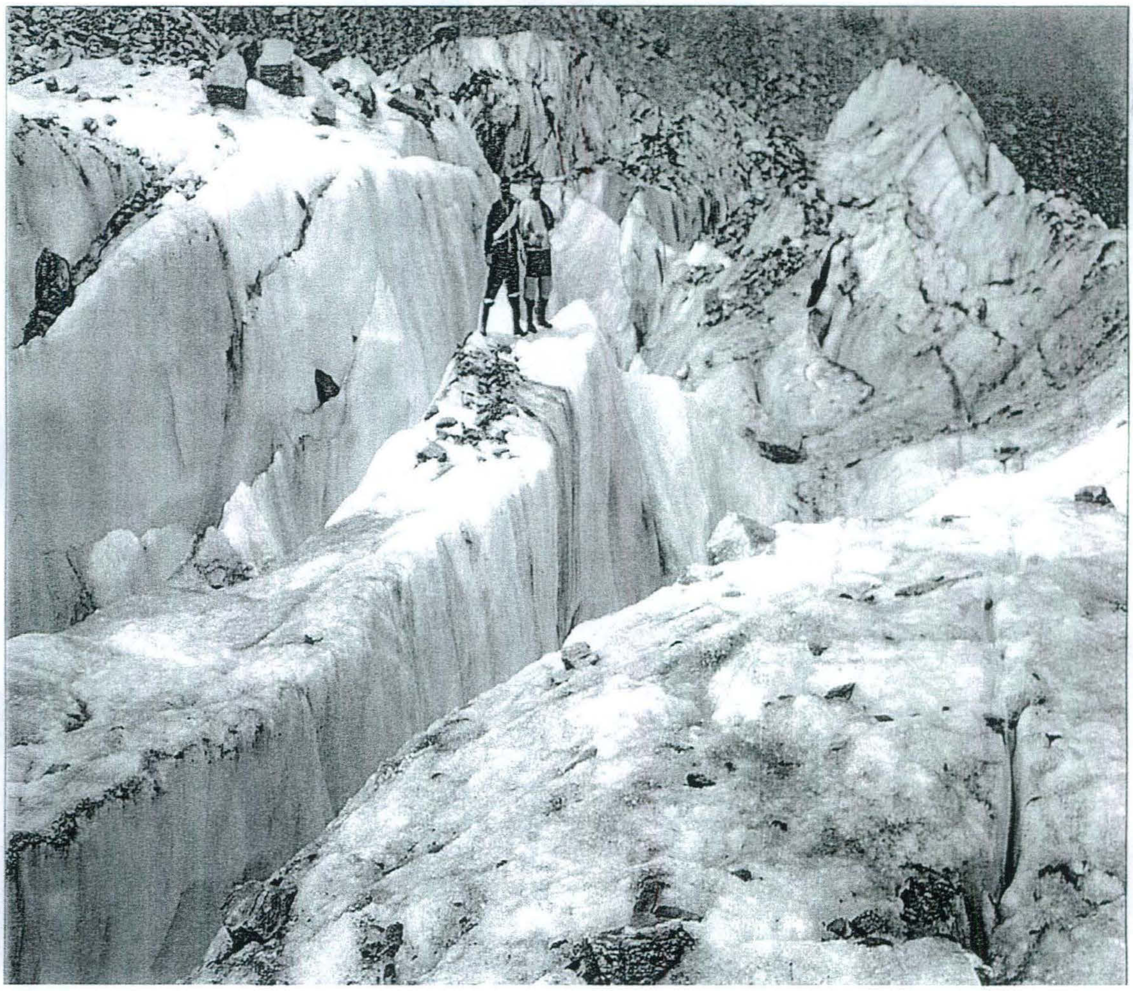


Plate 3.4: Huge crevasse in the ablation zone of Dokriani glacier

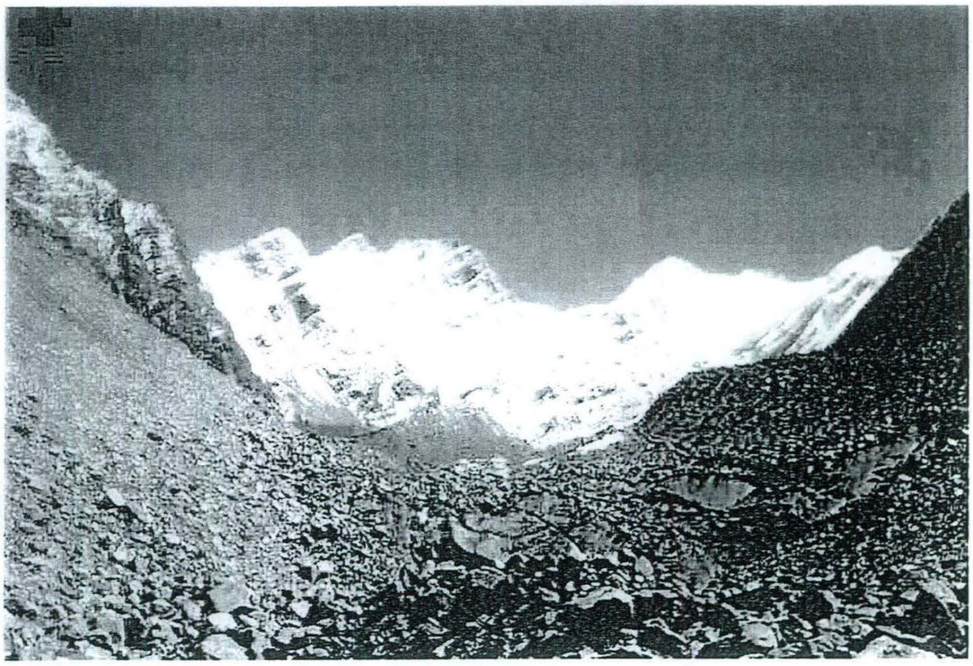


Plate 3.5: Ablation zone of Dokriani glacier covered with extensive morainic debris

3.6 GEOLOGY AND VEGETATION

Geology of the glacierised region of Bhagirathi valley (including Dokriani) consists of crystalline rocks particularly crystalline gneisses and schists of central crystalline axis with occurrence of carbonates and pyrite- shales and phyllites (Bhatt, 1963; Aggarwal and Kumar, 1973; Sarin et al., 1992). According to B. K. Bhatt (1963), the main rock types near Uttarkashi are fine-grained, compact massive quartzites and phyllites. The proportion of phyllites increases towards Bhatwari and Bhukki village. The study area is traversed by a major thrust; namely Main Central Thrust (MCT) on its southern side, which separates the Higher Himalayan rocks from the Lesser Himalayan rocks. Geological map of the area is given in Fig. 3.2

Din Gad has a dense mixed forest upto the height of 3000m, dominated by Rhododendron and Bhojpatra. Above 3000m the forest becomes sparse and near the snout hardly any vegetation is found.

3.7 DRAINAGE SYSTEM

There are two types of streams in the area, glacier- fed stream and ground water fed stream. These are perennial in nature. The Din Gad stream emerges from the Dokriani glacier and flows in the narrow valley carved by previous glacier extension. The stream joins the main Bhagirathi River at the east bank. The ground water fed streams emerge from the various dense forest sub-basins. Organic debris, sand, gravel, cobble, pebble and boulder cover the stream bed. The minimum flow in the Din Gad stream observed during the late winters slowly increases from June to September. During June-September the flow is recorded maximum in Din Gad due to high rate of snow and ice melting and monsoon precipitation. However, maximum discharge in groundwater fed stream is observed in spring time. The drainage map of the Gangotri basin showing Din Gad emerging from Dokriani glacier is shown in Fig 3.3

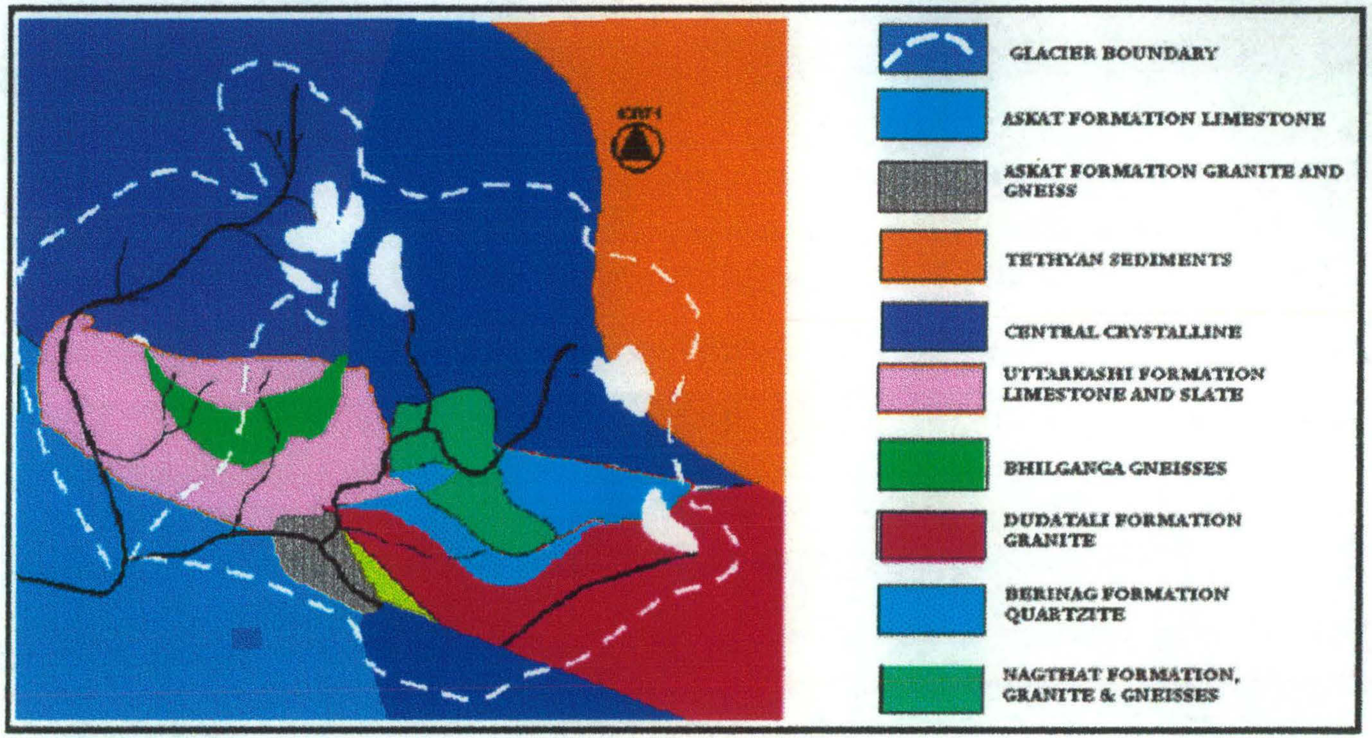
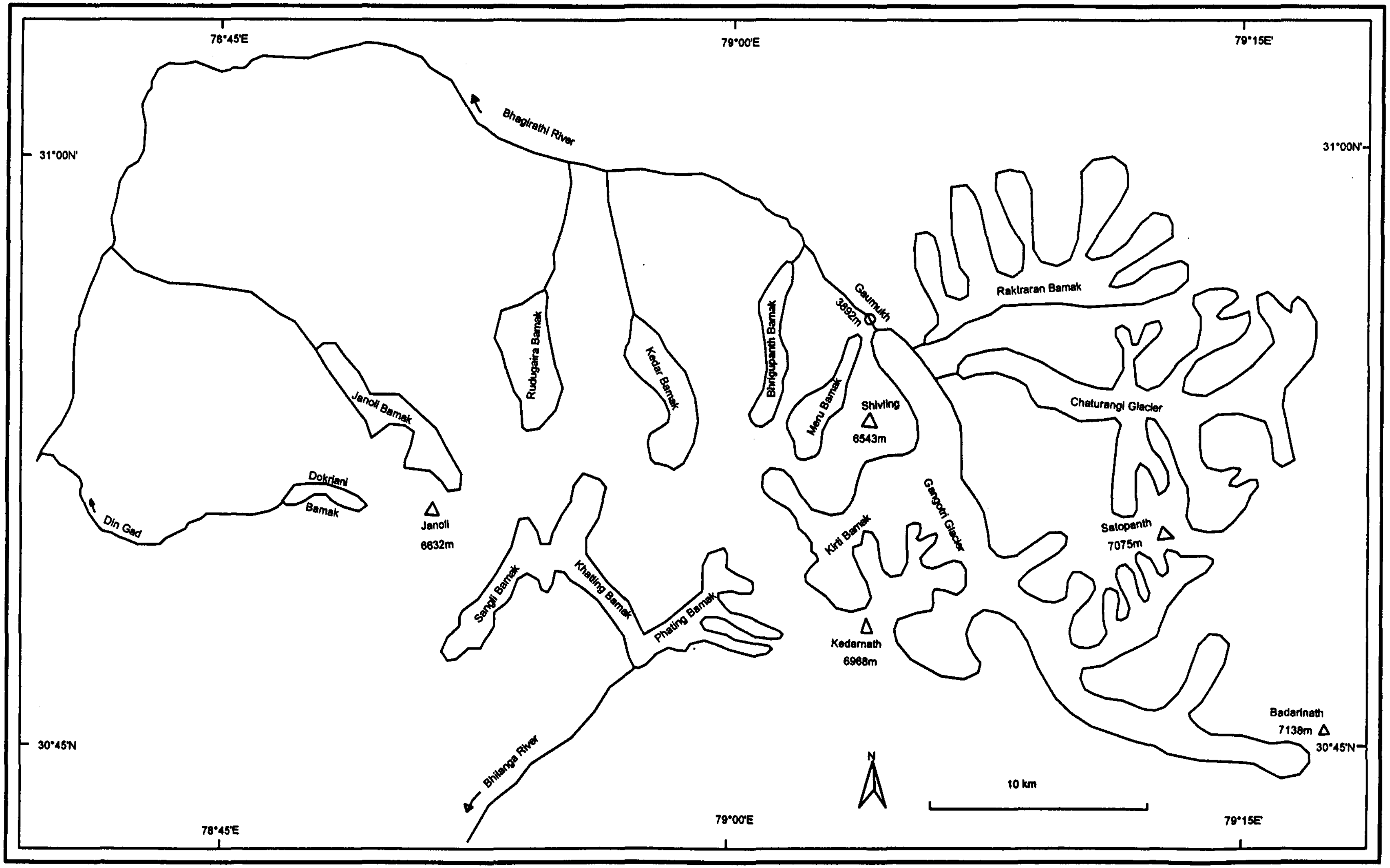


Fig. 3.2: Geological map of the study area (Aggarwal and Kumar, 1973)

Fig. 3.2 Drainage Map of Ganga Basin



3.8 CLIMATOLOGY

Due to variations of altitude, the climatic condition ranges from mild moist in the valley to cool temperate at higher altitude, the climate becomes progressively colder untill an extreme polar type is reached at the higher altitude on glacier (Singh, 1998). The altitude does not affect only temperature but precipitation too. Precipitation varies with sun facing site of the ridge, the sun facing slope receive more precipitation but less snowfall. It is reported that snowfall has more variation with elevation than rainfall (Singh,1998).

Climatic condition over the basin in a year can be divided in four distinctive seasons-Winter (December-January), Pre- monsoon (April-June), Monsoon (July-September), and Post-monsoon (October-November). The winter precipitation is generally in the form of snowfall in the Higher Himalaya. It is caused by extra-tropical weather system of mid-latitude probably originating from the Caspian and Mediterranean Sea and moves eastward with progress of winter season. The relative importance of winter precipitation increases with latitude and altitude. Generally the Pre-monsoon season lasts for a period of three months (April-June). In this season the convective orographic current causes few showers. Despite the sub-tropical latitude of the Himalayan Mountains their climate is controlled by the Indian monsoon regime through June to September. Moist air currents cause monsoon precipitation over the basin from the Bay of Bengal and Arabian Sea. Some time it is associated with both branches of monsoon trajectories. Normally the monsoon recedes by the end of September in the region. The post-monsoon season is characterised by little rainfall. The temperature in the winter season is below freezing point, whereas the maximum temperature is around 20°C in summer. Though accurate data is not available for snowfall, it is around 7-10m per annum in the higher reaches of the region.

3.9 ENVIRONMENTAL ASPECTS

The Dokriani glacier has undergone tremendous change since nineteen sixties. The recession of glacier is quite evident by the presence of morainic ridges and morainic materials all over the Glacier valley. Since 1962, this glacier has been receded about 600m at the rate of 15m per year in average. Due to high recession huge amount of sediment is carried down by meltwater stream. The Garhwal Himalaya since long time has been a centre of attraction for tourists from India and abroad. At the same time it offers huge opportunity to mountain lovers and people seeking adventurous sports and trekking. Mountaineering is also attracting lots of people to the glacier site. The human activities have its effect on the glacier. One can find pieces of papers, plastics, packing materials and other undesired materials left by trekkers and mountaineers all the way from road head to base camp and top on the glacier.

Grazing by Gujjar communities and shepherds during summer season is another aspect of degradation of the area. It was observed during fieldwork that many Gujjar communities are grazing their buffaloes on the meadows. Beside Gujjar communities, Shepherds from surrounding areas stay very close to the snout of the glacier for four to five months every year. During the period they use green shrubs wherever available as firewood. This widespread human intervention may lead to irreparable loss to the mountain ecosystem if not timely checked.

Chapter IV

MATERIAL AND METHODS

4.1 SAMPLING METHODOLOGY

Before proceeding to the fieldwork polyethylene bottles of 250 ml. capacity were washed in the laboratory with dilute HCl and then rinsed twice with distilled water. At the sampling site before collecting the meltwater, bottles were washed with the stream water. Meltwater samples were collected from near the gauging station, which is built about 600m downstream from the glacier portal. The water samples were collected following the methods of Ostrem (1975). The bottle was lowered into the stream and held at an angle of 45° upstream and held sufficiently long to fill the bottle almost to the neck. Two samples were collected each sampling day, one in the morning (600 hrs.) and another in the afternoon (1400 hrs.) However 24 hrs. samplings were done by using auto-water sampler. Soon after collecting the samples pH and EC was determined and samples were filtered through pre-weighed 0.45 µm Millipore filter papers. Analysis of HCO_3^- was carried out in the field by using autotitrator. For the analysis of rest of the ions, filtered water samples were brought to the Lab and kept in the cold room till the analysis.

4.2 EC AND pH:

pH of meltwater samples was measured in the field itself by Consort microcomputer (P-307) ion meter. Before measuring the pH, the electrodes were immersed in 0.1 N HCl for about 10 hours to ensure its stability. After rinsing the electrodes with distilled water, instrument was calibrated with a solution of pH 4.0 and 9.0. Once the electrode was calibrated, it was immersed in sample and pH of each sample was recorded.

Electrical conductivity also was measured in the field by using Pentax EC meter. It provides measurement of EC by a cell consisting of two platinum electrodes to which an alternating potential is applied. Before EC measurement, the instrument was calibrated and set for 0.01 M KCl standard. The conductivity of the samples was measured in μScm^{-1}.

4.3 DISCHARGE MEASUREMENT

Discharge measurements were carried out by using area-velocity method at Gauging site about 600 m downstream from the glacier portal. Discharge measurements are generally based upon water level reading on a vertical gauge fixed for the purpose at the bank of the meltwater stream. A gauge is a vertical rod marked in centimeters and meters placed so that the height of water level can be measured. For this purpose that portion of stream is selected where water is tranquil and less turbulent and fixed strong bedrock. The relationship between the water level at a given site and the actual discharge (m^3 s^{-1}) is determined by direct measurement of river flow for different gauge reading to obtain a graph of level vs. discharge, the rating curve for each measurement.

The velocity of stream water is measured by float method. A wooden float of 4"x 6" dimension was allowed to travel in stream between two fixed points established for the purpose. The time taken by the float to reach from one fixed point to another is noted by stopwatch. Therefore by measuring the velocity and stage reading the cross sectional area of the stream is calculated.

Once a rating curve is established all future gauge readings can be easily transformed to the discharge figures. Due to great variations in water discharge, numerous staff reading has been taken throughout the day. At the same time velocity measurements of the stream and the cross-sectional area are measured regularly, especially at a range of water level.

4.4 MEASUREMENT OF SUSPENDED SEDIMENT LOAD

Water samples collected at gauging station were filtered in the field by using pre-weighed 0.45 μm Millipore filter papers. The sediments so filtered were retained and determined their weight. The weight of sediment was determined by subtracting the weight of original filter paper from the weight of filter paper with sediment. Suspended sediment flux was obtained as the product of sampled sediment concentration (gl^{-1})

and hourly average discharge (m^3s^{-1}). Daily sediment load was computed from the 24 hrs. suspended sediment flux values. For calculation of total sediment yield in the ablation season, mean monthly values for the ablation season were taken into account

4.5 ANALYTIVAL METHODS

Bicarbonate

Bicarbonate was determined in the field by using potentiometric titration method .In this method no indicator was used to signify the end point, instead the pH of the samples as well as that of the standard solution was maintained at 4.5 by adding HCl 0.004N.The end point of the reaction was attained when the solution comes at a pH of 4.5. A graph was plotted for standard concentration against the volume of HCI consumed. The concentration of the samples was determined from the graph plotted for standard.

Chloride

Chloride was determined by mercury (II) thiocyanate method (Florence and Ferrar, 1971). This method involves the reaction of chloride with mercury (II) thiocyanate to form chloromercurate (II) complex ion with the liberation of thiocyanate ions, which then reacts with iron (III) to give the red colour. 20 ml of each standard and sample was pipetted out into a 25 ml volumetric flask. 2 ml of iron (III) nitrate reagent (prepared by dissolving 15.1 gm of $Fe(NO_3)_3 . 9H_2O$ in 45ml of 72% perchloric acid and diluted to 100 ml. with distilled water). After mixing well, solution was poured into the absorbance cell of the spectrophotometer and reading was taken against a reagent blank at 460 nm after 5 minutes and the chloride concentration was estimated by comparing reading with calibration curve prepared by carrying chloride standard through the entire procedure.

Sulphate

Sulphate ion conc. was measured by turbiditric method (APHA, 1985). The method is based on the principle that SO_4^{2-} is precipitated in an acetic medium with $BaCl_2$, so as to form $BaSO_4$ crystals of uniform size. While adding $BaCl_2$ the system must be subjected to stir for 60 sec. The crystals of $BaSO_4$ so formed are allowed to rest for four minutes and then the samples are subjected to the measurement of SO_4^{2-} conc. by placing the sample in the photometric absorbance cell at 420 nm and turbidity is measured. 100 ml of standards and samples were measured in a volumetric flask and 20 ml of buffer solution (prepared by dissolving 30 gm of $MgCl_2.6H_2O$, 5 gm of sodium acetate, 1 gm of potassium nitrate and 0.111 gm of sodium sulphate and 20 ml of acetic acid in 500 ml of distilled water and then the total volume was made to 1000 ml) was added and mixed with the help of magnetic stirrer. While stirring, a spoonful of $BaCl_2$ crystals were added. This was stirred for 60 second with constant speed. After the stirring period, solutions were allowed to rest for four minutes and then placed into the absorbance cell of the photometer and absorbance readings were taken at 420 nm. Sulphate concentrations were determined by comparing readings with calibration curve prepared by carrying sulphate standards through the entire process.

Dissolved silica (H_2SiO_4)

Dissolved silica was determined by molybdosilicate method (APHA, 1985). 20ml of ammonium molybdate solution (prepared by dissolving 2.0 gm of ammonium molybdate in 10 ml distilled water and 6.0 ml of conc. HCl and volume was made to 100 ml) and 15 ml of reducing agent (prepared by mixing 100 ml of metol sulphite solution; 60 ml of 10 % oxalic acid and 120 ml of 25% H_2SO_4 and volume was made to 300 ml.) were added. The samples were stirred well and kept for three hours to complete the reaction. The optical density was measured for standard water samples at 812 nm by using UV/ VIS spectrophotometer.

Major cations

The analysis of major cations was carried out on GBC 906 Atomic Absorption Spectrophotometer (AAS). Calcium and Magnesium were analyzed in absorption mode and Sodium and Potassium in the emission mode.

4.6 DYE TRACER METHODS

Dye tracer experiments were conducted to find out the hydrological system of the glacier and to assess the discharge of glacier meltwater during ablation season. Dye tracer studies were conducted by using Rhodomine-WT dye of 1ppm concentration. 40 ml of dye was injected into the moulins (denoted by symbol J) in July and August and 50 ml in September 2000. The concentration of Rhodamine in the stream was measured by using a continuous flow cuvette at an interval of 2 minutes on 8 and 9 July and at an interval of 5 minutes on all subsequent injection dates by Turner Design Fluorometer, model no.10-AU-005-CE. The instrument used a continuous 25 mm flow cell or cuvette and was calibrated with stream water as blank and 20 parts per billion (20 ppb) standard solutions. The measurements were done in the manual mode with automatic temperature compensation. The stream discharges at the time of dye injection, dye peak and average dye concentration for the experiment were measured.

Ten experiments were conducted at three moulins at 930m, 1700m, and 2300m up-glacier respectively from the measurement site (fluorometer station). In the moulin 1 (J1) two experiments were conducted on 8 July and 20 August at 11.31 hrs. and 10.35 hrs. respectively. On moulin 2 (J2) experiments conducted were on 9 July and 21 August with injection time of 11.04 hrs and 10.40 hrs respectively. On moulin 3 (J3) six experiment were conducted on 13 July, 23 August, 14 September, 18 September, 24 September and 28 September. The travel time of the dye was measured by fluorometer placed 600 m downstream from the glacier snout. As dye passes through internal drainage system of the glacier it gets diluted and changes in dye concentration was measured by the fluorometer. The time-concentration relationships obtained from dye injections during all the experiments have been plotted in curves (in chapter result and discussion).

Chapter V

RESULT AND DISCUSSION

5.1 HYDROLOGICAL CHARACTERISTICS OF MELTWATER

The discharge measurements carried out in the year 1999, 2000 and 2001 revealed diurnal and seasonal variations. Discharge gradually increases from April/May and reaches its peak in July/August and then starts decreasing. Ablation months of July and August experience the highest discharge. The mean values of discharge observed for the months of July and August 1999 were 4.10 m^3s^{-1} and 3.66 m^3s^{-1} respectively. The average discharge computed for the ablation season of 1999 was 3.41 m^3s^{-1}. For the ablation season 2000, the mean discharge values for the months of July and August were 7.0 m^3s^{-1}, 5.7 m^3s^{-1} respectively, while for 2001 it was 2.5 m^3s^{-1} and 3.1 m^3s^{-1} respectively. The average discharge computed for the ablation season 2000 was 5.4 m^3s^{-1} and that for the ablation season 2001 was 2.90 m^3s^{-1}. The values observed above have direct relationship with the amount and intensity of rainfall. The month of June is generally the period of no rain or very less rain. Only 90mm of rainfall have been recorded in the month of June 2001, while in June 1999 there was no rainfall. Most of the rainfall occurs in the months of July and August. The amount of rainfall recorded in the month of July 1999, 2000, 2001 was 284mm, 587mm and 307mm respectively, while total rainfall for the seasons 1999, 2000 and 2001 was recorded to be 630mm, 1279mm and 542mm respectively. All events related with high flow occurred in the months of July and August confirming that these events were due to combined rain and glacier melt contribution. Hydrographs (Fig 5.36 to 5.38) of the ablation season 1999, 2000 and 2001 show a significant contribution of rainfall towards the runoff during July and August. During monsoon season the icemelt rate reduces due to the thick cloud cover in the region, but with the increased precipitation higher discharge is sustained. Therefore both temperature and distribution of rainfall control the runoff behaviour of the glacier basin.

5.2 HYDROCHEMICAL INVESTIGATIONS

EC and pH

The electrical conductivity, which is a measure of the ability of a solution to conduct electrical current, transferred by ions in solution, is related to the concentration and nature of ions present in the solution, and the total dissolved solids is proportional to the EC of a solution. The electrical conductivity observed in the ablation seasons (1999 to 2001) reflects seasonal as well as diurnal variations. The range of variation of EC of the meltwater during the ablation season (1999 to 2001) was 7.0 to 60 ìS/cm with an average value of 25.0, 38.0, and 33.0 µS/cm. for the ablation seasons 1999, 2000 and 2001 respectively. The average pH values observed during the ablation seasons 1999, 2000 and 2001 were 7.32, 7.10 and 7.26 respectively. This does not show much variation for the different years. Very less variation in pH has also been reported for the years 1992-1995 (Hasnain, 1995).

5.3 RAIN WATER CHEMISTRY

The studies on the chemical composition of aerosol and precipitation in the Himalaya are limited on both temporal and spatial scales. The precipitation scavenging plays an important role in reducing aerosol concentration in the Himalaya (Shreshtha et al., 2000). The quantitative estimates of past atmospheric chemical composition based on glacio-chemical data depend greatly on the knowledge of the relationship between the chemistry of the precipitation and that of the air masses within which it forms. The rainwater samples collected in the ablation season 2000 were analysed for determination of major ionic species. The immediate analysis of the collected rain samples reveals the seasonal average of EC as 6.0 µS/cm with a seasonal variation of 1.9 -17.3 µS/cm and standard deviation of 3.6. The average pH of the rainwater was 5.0, indicating the dissolution of H^+ producing ionic species in the rainwater in the atmosphere.

The results show the order of anions (Table 5.1) present in the rainwater as $NO_3^- > SO_4^{2-} > HCO_3^- > Cl^-$. The average concentration of bicarbonate observed was about 18 ìeq/l ranging from 5.2 – 60 µeq/l with standard deviation of 8.0. The likely source of bicarbonate in rainwater is the dissolution of carbonic acid formed in the atmosphere by the dissolution of CO_2 in the water vapour. In the early monsoon period, due to high aerosol content, HCO_3^- concentration was high and it decreased as the monsoon progressed. Chloride component showed very high variability in the early monsoon, lesser in the middle, while the variability increased again in late September. Higher variability in the early season is related to local air masses; while in mid July and August the high concentration and low variability during the period could be related to monsoon trajectory (Shreshtha et al., 2002). The average conc. of nitrate and sulphate observed were 22 µeq/l and 20 µeq/l respectively. In the monsoon period the concentrations of NO_3^- and SO_4^{2-} display significant variation. It could be related to the sea salt source and biogenic exodus in the basin, anthropogenic flux from SW monsoon trajectories and use of large-scale fertilizers in the region (Blanched, 1982).

The cations in rainwater samples were in the order of $Ca^{2+} > Na^+ > Mg^{2+}$. The average concentrations were found to be 37µìeq/l, 23.0 ìeq/l for Ca^{2+} and Na^+ respectively. For determining the source of cations in the monsoon rainwater, the ratio Na^+/Cl^-, Ca^{2+}/Cl^- and Mg^{2+}/Cl^- have been used by various authors (Khemani et al., 1985; Khemani et al., 1989). The results obtained by these authors have shown that soil is a major contributor of aerosol in the Indian atmosphere and high dust loading in the Indian atmosphere can elevate the concentration in the precipitation, particularly Ca^{2+}, Mg^{2+} and Na^+ (Khemani et al., 1989). However the dust loading in the Himalaya is low which results in low concentration of dissolved solids in the rainwater in comparison to the rainwater in the Gangetic plain and in the peninsula (Shrestha et al., 2002). The ratio for Na^+/ Cl^- in the rainwater samples near the ocean is 0.58, quite lower than that for the rainwater samples in the study area. The study indicated that the source of ionic content in high altitude Himalayan region is the crustal input from the surrounding areas. Significant seasonal variations have been found in Na^+/Cl^- ratio.

5.4 CHEMICAL CHARACTERISTICS OF MELTWATER

The analysis of meltwater has revealed that Ca^{2+} is the dominant cation (Table 5.2), whereas HCO_3^- and SO_4^{2-} are the dominant anions. The content of K^+ is least among cations. Among anions, SO_4^{2-} is the dominant ion in the meltwater for the year 1999

Table 5.1: EC, pH and Ionic cocentration of major cations and anions in the rainfall samples

S.N	Date	EC	pH	HCO_3^-	SO_4^{2-}	NO_3^-	Cl^-	Na^+	Mg^{2+}	Ca^{2+}
1	30-Jul	13.5	6.4	42.0	25.9	35.6	6.8	30.2	8.0	44.4
2	2-Jul	10.2	6.1	37.8	17.9	33.0	11.5	43.2	12.0	60.7
3	4-Jul	10.3	5.7	23.1	17.8	37.3	4.7	24.1	36.7	77.2
4	7-Jul	5.3	5.3	21.0	22.1	24.8	4.5	12.1	1.5	16.5
5	7-Jul	10.8	5.7	52.5	17.5	19.5	13.1	16.7	19.0	71.7
6	8-Jul	4.3	5.4	21.0	18.6	21.8	9.3	10.2	4.5	27.6
7	9-Jul	5.1	5.5	15.1	17.8	19.3	11.9	24.8	0.5	5.5
8	10-Jul	5.9	5.5	21.4	19.1	20.0	11.4	20.9	1.1	22.1
9	28-Jul	8.1	5.0	16.8	24.7	19.3	11.2	23.2	0.7	27.6
10	30-Jul	4.5	4.9	17.0	18.5	19.1	12.9	20.9	ND	ND
11	31-Jul	4.5	4.7	14.7	20.9	23.5	14.5	16.0	ND	ND
12	1-Aug	4.1	4.9	12.6	14.8	20.0	12.0	21.5	5.7	22.1
13	2-Aug	3.5	4.8	23.1	19.4	19.5	11.6	21.3	3.2	16.5
14	4-Aug	3.3	4.9	18.9	28.0	19.7	11.3	35.6	3.2	55.1
15	4-Aug	5.2	5.0	10.5	14.9	21.1	12.6	41.7	4.7	16.5
16	4-Aug	17.4	5.4	12.6	12.6	19.5	12.2	ND	ND	ND
17	8-Aug	9.4	5.7	10.9	18.6	38.3	6.8	20.6	19.5	55.1
18	9-Aug	5.1	5.5	14.7	16.1	19.1	12.4	25.8	15.0	71.7
19	10-Aug	3.9	5.3	17.4	13.9	22.4	12.5	6.8	ND	44.1
20	11-Aug	5.8	5.0	21.0	10.8	19.5	13.5	14.4	0.5	11.0
21	12-Aug	10.2	5.0	27.3	23.5	19.7	13.2	21.9	21.8	55.1
22	13-Aug	7.3	5.1	36.8	16.4	20.4	12.6	35.4	21.9	66.2
23	14-Aug	4.1	5.5	22.1	18.6	19.3	11.8	19.6	12.1	27.6
24	15-Aug	7.0	5.5	15.8	24.9	20.0	11.7	22.8	1.2	ND
25	15-Aug	8.3	5.9	16.8	20.1	19.5	12.0	21.1	6.2	33.1
26	17-Aug	4.3	5.9	14.7	15.8	19.5	11.6	22.2	5.7	27.6
27	18-Aug	4.7	6.0	15.5	17.0	19.3	12.1	20.2	2.7	ND
28	19-Aug	2.6	5.9	13.7	19.1	21.1	11.9	22.7	ND	22.1
29	21-Aug	3.6	5.3	25.2	18.2	19.8	12.1	18.5	ND	ND
30	21-Aug	2.9	5.6	16.8	16.1	25.2	11.6	24.1	7.7	ND
31	23-Aug	2.0	5.7	17.0	17.8	19.3	12.0	23.3	0.5	ND
32	28-Aug	3.3	5.4	12.2	21.0	17.7	13.2	28.2	0.2	ND
33	30-Aug	6.4	5.8	14.9	15.7	34.1	12.1	30.4	157.8	154.4
34	31-Aug	2.9	5.6	15.8	24.4	19.7	12.4	21.4	6.8	11.0
35	8-Sep	2.7	5.7	10.7	20.0	23.1	14.1	24.3	36.4	71.7
36	12-Sep	6.1	5.6	13.0	17.5	23.7	13.3	22.4	2.0	16.5
37	12-Sep	3.4	6.6	23.1	27.5	20.9	12.9	ND	ND	ND
38	13-Sep	2.1	6.6	23.3	24.0	21.1	13.1	48.1	ND	22.1
39	18-Sep	13.5	6.1	25.2	29.7	22.6	11.6	20.5	5.5	30.0
40	20-Sep	5.6	5.7	25.0	23.4	21.4	11.9	26.4	73.6	42.0
41	21-Sep	8.1	5.3	25.2	24.0	27.0	10.3	29.9	ND	27.6
42	22-Sep	5.9	5.9	13.7	14.2	29.8	9.8	36.6	8.2	ND
43	22-Sep	4.8	6.1	15.1	20.9	27.3	12.5	39.1	106.2	41.3
44	23-Sep	3.9	6.4	21.4	19.4	21.6	6.2	25.8	79.8	57.0
45	24-Sep	17.0	5.7	23.1	21.6	31.1	5.6	26.7	90.5	48.0
46	25-Sep	7.8	6.5	15.3	17.8	22.3	9.9	ND	ND	ND

Avg		6.1	5.5	18.4	20.0	22.0	10.9	23.6	20.4	36.4
Max		17.4	6.6	52.5	33.7	38.3	14.5	48.1	157.8	154.4
Min		1.9	4.7	5.9	10.8	17.7	2.8	0.0	0.2	0.0
Std		3.6	0.5	8.3	4.4	4.5	2.8	9.2	33.0	28.1

All units in μeq/l, EC in μS/cm

followed by HCO_3^-. All ionic contents show diurnal as well as seasonal variations.

Bicarbonate: Bicarbonate is the major contributor of alkalinity in stream water. It acts as buffer to restrain the change in pH of the medium. The average concentration of Bicarbonate in the meltwater samples for the ablation season 1999 was found to be 0.151 meq/l with the seasonal variation of 0.098 meq/l to 0.279 meq/l and standard variation of 0.065. The mean monthly concentration of bicarbonate in the year 1999 was 0.215 meq/l, 0.130 meq/l, 0.124 meq/l, and 0.218 meq/l for the months of June, July, August and September respectively. The mean monthly concentrations of bicarbonate were 10.40ppm, 12.45ppm, 10.09ppm for the months of July, August and September 2000 and 5.40ppm, 8.373ppm, 5.92ppm, 8.04ppm for the months of June, July, August and September 2001 respectively (Table 5.3 and 5.4). It has been observed (Fig.5.1) that in the ablation season of 1999, both HCO_3^- and SO_4^{2-} follow almost the same trend from June to September, the concentrations of both the constituents decreasing as the monsoon progresses, with a slight increase in September.

Sulphate: Sulphate is a member of acidity producing anion in the water. The source of sulphate in the glacierised basin is from the oxidation of sulphide mineral and atmospheric deposition. The atmospheric deposition of sulphur is responsible for acidification of many fresh water bodies. In the glacial meltwater, the contribution of sulphur from atmospheric deposition is of minor significance because valley glaciers are situated far away from sources of pollution. Therefore, in meltwater the main source of sulphate is sulphide minerals present in the rocks of glacier basin. The average concentration of sulphate in the meltwater of 1999 was 0.307meq/l and showed seasonal variation of 0.212 meq/l to 0.585 meq/l with standard variation of 0.114. The mean monthly concentration of sulphate for the month of June, July, August and September was found to be 0.498 meq/l, 0.297 meq/l, 0.225 meq/l, 0.283 meq/l respectively. The average concentration for the ablation season 1999 was 0.325meq/l.

Chloride: The available literature suggests that the atmospheric precipitation is the

Table 5.2: Meltwater characteristics of Dokriani glacier for ablation season 1999

DAY/TIME	HCO_3^-	SO_4^{2-}	Cl^-	H_4SiO_4	Ca^{2+}	Mg^{2+}	Na^+	K^+
14.06.99								
6AM	0.269	0.427	0.025	7.980	0.243	0.098	0.043	0.037
4PM	0.279	0.535	0.026	8.940	0.257	0.083	0.387	0.046
15.06.99								
6AM	0.210	0.415	0.025	8.170	0.240	0.100	0.040	0.042
4PM	0.272	0.554	0.026	8.940	0.261	0.085	0.364	0.044
16.06.99								
6AM	0.202	0.442	0.025	8.170	0.245	0.100	0.042	0.042
4PM	0.274	0.560	0.026	9.130	0.254	0.085	0.376	0.046
17.06.99								
6AM	0.213	0.448	0.025	8.170	0.246	0.095	0.040	0.043
4PM	0.270	0.585	0.026	9.130	0.252	0.080	0.364	0.047
18.60.99								
6AM	0.246	0.454	0.025	8.170	0.245	0.093	0.042	0.044
4PM	0.269	0.573	0.026	9.130	0.251	0.083	0.376	0.034
19.06.99								
6AM	0.193	0.448	0.025	8.170	0.240	0.090	0.040	0.029
4PM	0.243	0.573	0.026	9.900	0.249	0.085	0.364	0.041
20.06.99								
6AM	0.205	0.421	0.025	7.980	0.239	0.093	0.043	0.044
4PM	0.261	0.554	0.026	10.290	0.242	0.085	0.387	0.032
21.06.99								
6AM	0.239	0.421	0.025	7.980	0.237	0.095	0.040	0.043
4PM	0.243	0.510	0.025	10.480	0.245	0.088	0.364	0.039
22.06.99								
6AM	0.230	0.427	0.026	7.790	0.237	0.090	0.039	0.035
4PM	0.236	0.517	0.026	10.670	0.246	0.083	0.352	0.042
23.06.99								
6AM	0.238	0.408	0.026	7.980	0.236	0.095	0.044	0.022
4PM	0.218	0.504	0.026	10.870	0.242	0.080	0.399	0.039
24.06.99								
6AM	0.216	0.573	0.026	11.060	0.222	0.083	0.387	0.033
4PM	0.228	0.454	0.025	8.170	0.218	0.088	0.044	0.038
25.06.99								
6AM	0.238	0.567	0.026	11.830	0.222	0.085	0.399	0.036
4PM	0.167	0.448	0.026	8.370	0.218	0.090	0.046	0.040
26.06.99								
6AM	0.164	0.442	0.026	8.560	0.215	0.085	0.047	0.044
4PM	0.210	0.504	0.026	10.100	0.215	0.085	0.423	0.042
27.06.99								
6AM	0.182	0.383	0.025	8.750	0.207	0.085	0.046	0.043
4PM	0.210	0.517	0.025	10.100	0.207	0.083	0.411	0.028
28.06.99								
6AM	0.192	0.402	0.025	8.750	0.173	0.083	0.050	0.051
4PM	0.221	0.554	0.026	9.900	0.168	0.080	0.446	0.046

Continued.....

DAY/TIME	$HCO3^-$	SO_4^{2-}	Cl^-	H_4SiO_4	Ca^{2+}	Mg^{2+}	Na^+	K^+
29.06.99								
6AM	0.189	0.365	0.025	8.370	0.176	0.070	0.044	0.042
4PM	0.220	0.460	0.025	9.900	0.173	0.075	0.399	0.034
30.06.99								
6AM	0.197	0.321	0.025	8.560	0.179	0.075	0.043	0.033
4PM	0.223	0.454	0.026	9.900	0.176	0.078	0.387	0.040
01.07.99								
6AM	0.170	0.302	0.025	8.560	0.177	0.080	0.038	0.018
4PM	0.226	0.448	0.025	9.900	0.174	0.080	0.340	0.042
02.07.99								
6AM	0.164	0.296	0.025	8.560	0.177	0.083	0.038	0.033
4PM	0.216	0.352	0.026	9.710	0.188	0.078	0.340	0.047
03.07.99								
6AM	0.167	0.321	0.025	7.980	0.176	0.080	0.037	0.030
4PM	0.210	0.396	0.026	8.170	0.186	0.080	0.329	0.053
04.07.99								
6AM	0.161	0.308	0.024	7.980	0.168	0.078	0.038	0.034
4PM	0.167	0.390	0.026	7.980	0.185	0.080	0.340	0.046
05.07.99								
6AM	0.167	0.290	0.026	7.980	0.171	0.080	0.037	0.029
4PM	0.190	0.408	0.025	7.790	0.191	0.083	0.329	0.048
06.07.99								
6AM	0.125	0.271	0.026	7.790	0.173	0.073	0.035	0.039
4PM	0.170	0.421	0.025	7.980	0.192	0.075	0.317	0.048
07.07.99								
6AM	0.103	0.277	0.026	7.790	0.174	0.073	0.037	0.034
4PM	0.185	0.390	0.025	8.170	0.186	0.078	0.329	0.042
08.07.99								
6AM	0.126	0.206	0.026	7.600	0.176	0.075	0.035	0.029
4PM	0.156	0.352	0.026	8.170	0.201	0.075	0.317	0.041
09.07.99								
6AM	0.131	0.240	0.026	7.400	0.177	0.078	0.037	0.042
4PM	0.138	0.321	0.026	8.370	0.204	0.075	0.329	0.035
10.07.99								
6AM	0.108	0.246	0.026	7.400	0.179	0.080	0.035	0.041
4PM	0.115	0.315	0.026	8.560	0.203	0.080	0.317	0.033
11.07.99								
6AM	0.123	0.258	0.026	7.400	0.177	0.083	0.037	0.028
4PM	0.118	0.333	0.025	8.750	0.201	0.078	0.329	0.038
12.07.99								
6AM	0.098	0.265	0.026	7.210	0.182	0.070	0.034	0.042
4PM	0.131	0.308	0.025	8.940	0.197	0.080	0.305	0.039
13.07.99								
6AM	0.102	0.240	0.026	7.790	0.176	0.073	0.035	0.040
4PM	0.128	0.290	0.025	7.980	0.194	0.075	0.317	0.037
14.07.99								
6AM	0.098	0.265	0.026	7.980	0.173	0.075	0.035	0.022
4PM	0.102	0.271	0.025	7.790	0.192	0.078	0.313	0.032

Continued…..

DAY/TIME	$HCO3^-$	SO_4^{2-}	Cl^-	H_4SiO_4	Ca^{2+}	Mg^{2+}	Na^+	K^+
15.07.99								
6AM	0.072	0.290	0.026	7.980	0.171	0.078	0.034	0.045
4PM	0.085	0.296	0.025	7.790	0.192	0.078	0.305	0.029
16.07.99								
6AM	0.077	0.321	0.026	7.790	0.170	0.075	0.034	0.036
4PM	0.120	0.283	0.025	7.980	0.191	0.080	0.305	0.028
17.07.99								
6AM	0.066	0.271	0.026	7.980	0.168	0.073	0.037	0.016
4PM	0.085	0.302	0.025	7.210	0.189	0.080	0.329	0.033
18.07.99								
6AM	0.067	0.258	0.026	8.170	0.173	0.070	0.035	0.040
4PM	0.084	0.296	0.026	7.020	0.188	0.078	0.317	0.022
19.07.99								
6AM	0.095	0.240	0.026	8.170	0.171	0.073	0.034	0.038
4PM	0.121	0.219	0.026	7.210	0.186	0.078	0.305	0.044
20.07.99								
6AM	0.089	0.219	0.026	7.980	0.170	0.074	0.033	0.018
4PM	0.098	0.219	0.026	7.210	0.179	0.080	0.293	0.034
21.07.99								
6AM	0.087	0.219	0.026	7.980	0.168	0.075	0.034	0.040
4PM	0.100	0.225	0.026	7.210	0.177	0.078	0.305	0.029
22.07.99								
6AM	0.067	0.213	0.026	7.980	0.167	0.075	0.035	0.017
4PM	0.090	0.213	0.026	7.400	0.168	0.080	0.317	0.037
23.07.99								
6AM	0.085	0.206	0.025	7.980	0.165	0.080	0.037	0.042
4PM	0.141	0.246	0.026	7.790	0.170	0.078	0.329	0.040
24.07.99								
6AM	0.085	0.225	0.026	7.790	0.170	0.078	0.035	0.021
4PM	0.131	0.240	0.026	7.980	0.177	0.080	0.317	0.044
25.07.99								
6AM	0.079	0.206	0.026	7.790	0.171	0.080	0.035	0.014
4PM	0.108	0.219	0.027	7.790	0.176	0.078	0.317	0.040
26.07.99								
6AM	0.084	0.233	0.026	7.790	0.173	0.083	0.033	0.042
4PM	0.136	0.246	0.026	7.400	0.174	0.078	0.293	0.042
27.07.99								
6AM	0.082	0.246	0.026	7.790	0.174	0.085	0.033	0.041
4PM	0.128	0.240	0.027	7.020	0.171	0.080	0.293	0.042
28.07.99								
6AM	0.084	0.200	0.026	7.790	0.179	0.083	0.034	0.029
4PM	0.100	0.225	0.027	6.830	0.170	0.083	0.305	0.041
29.07.99								
6AM	0.098	0.175	0.026	7.790	0.182	0.080	0.034	0.036
4PM	0.121	0.213	0.027	7.020	0.177	0.083	0.305	0.045
30.07.99								
6AM	0.113	0.181	0.026	7.790	0.180	0.083	0.034	0.041
4PM	0.116	0.225	0.025	6.830	0.176	0.080	0.305	0.033

Continued…..

DAY/TIME	$HCO3^-$	SO_4^{2-}	Cl^-	H_4SiO_4	Ca^{2+}	Mg^{2+}	Na^+	K^+
31.07.99								
6AM	0.087	0.188	0.026	7.400	0.177	0.085	0.037	0.040
4PM	0.090	0.200	0.025	6.830	0.177	0.083	0.329	0.030
01.08.99								
6AM	0.084	0.240	0.026	7.400	0.174	0.085	0.038	0.042
4PM	0.093	0.200	0.026	7.400	0.179	0.085	0.340	0.028
02.08.99								
6AM	0.085	0.225	0.026	7.210	0.171	0.085	0.035	0.029
4PM	0.102	0.194	0.025	7.790	0.176	0.085	0.317	0.041
03.08.99								
6AM	0.082	0.200	0.026	7.210	0.170	0.080	0.034	0.035
4PM	0.102	0.194	0.025	7.980	0.179	0.085	0.305	0.039
04.08.99								
6AM	0.084	0.181	0.026	7.020	0.168	0.083	0.037	0.041
4PM	0.110	0.188	0.025	7.790	0.180	0.088	0.329	0.044
05.08.99								
6AM	0.087	0.200	0.026	7.210	0.171	0.090	0.039	0.024
4PM	0.113	0.181	0.026	6.830	0.182	0.088	0.352	0.044
06.08.99								
6AM	0.082	0.240	0.026	7.210	0.170	0.093	0.038	0.046
4PM	0.098	0.194	0.026	6.630	0.183	0.088	0.340	0.035
07.08.99								
6AM	0.089	0.194	0.026	7.210	0.177	0.093	0.038	0.029
4PM	0.098	0.206	0.026	6.830	0.185	0.085	0.340	0.046
08.08.99								
6AM	0.084	0.194	0.026	7.210	0.179	0.095	0.037	0.036
4PM	0.085	0.206	0.026	7.020	0.185	0.090	0.329	0.042
09.08.99								
6AM	0.085	0.200	0.026	7.020	0.174	0.095	0.035	0.038
4PM	0.089	0.206	0.025	7.020	0.150	0.090	0.317	0.033
10.08.99								
6AM	0.084	0.206	0.026	7.020	0.176	0.095	0.034	0.039
4PM	0.085	0.213	0.025	7.210	0.182	0.090	0.305	0.046
11.08.99								
6AM	0.082	0.194	0.026	7.400	0.171	0.093	0.034	0.041
4PM	0.108	0.206	0.026	8.170	0.183	0.085	0.305	0.032
12.08.99								
6AM	0.082	0.175	0.026	7.600	0.170	0.093	0.033	0.041
4PM	0.092	0.233	0.026	8.560	0.185	0.088	0.293	0.038
13.08.99								
6AM	0.079	0.175	0.026	7.400	0.177	0.090	0.031	0.015
4PM	0.125	0.225	0.026	7.980	0.186	0.083	0.282	0.026
14.08.99								
6AM	0.075	0.194	0.026	7.210	0.179	0.088	0.034	0.024
4PM	0.105	0.200	0.026	7.020	0.186	0.083	0.305	0.044

Continued…..

DAY/TIME	$HCO3^-$	SO_4^{2-}	Cl^-	H_4SiO_4	Ca^{2+}	Mg^{2+}	Na^+	K^+
15.08.99								
6AM	0.103	0.240	0.025	7.980	0.182	0.093	0.035	0.044
4PM	0.130	0.194	0.026	8.370	0.186	0.088	0.317	0.040
16.08.99								
6AM	0.100	0.131	0.026	7.980	0.183	0.093	0.037	0.024
4PM	0.103	0.188	0.026	8.170	0.189	0.090	0.329	0.045
17.08.99								
6AM	0.128	0.144	0.026	7.980	0.186	0.095	0.037	0.044
4PM	0.121	0.169	0.026	8.170	0.192	0.090	0.329	0.041
18.08.99								
6AM	0.115	0.194	0.026	7.790	0.188	0.095	0.039	0.040
4PM	0.118	0.181	0.026	8.170	0.192	0.093	0.352	0.036
19.08.99								
6AM	0.095	0.246	0.025	7.790	0.189	0.093	0.040	0.046
6PM	0.000	0.144	0.026	7.600	0.176	0.000	0.000	0.000
20.08.99								
6AM	0.130	0.258	0.026	7.790	0.191	0.090	0.042	0.042
4PM	0.205	0.194	0.026	7.980	0.194	0.093	0.376	0.046
21.08.99								
6AM	0.133	0.240	0.026	7.790	0.192	0.090	0.043	0.035
4PM	0.189	0.271	0.026	7.790	0.194	0.095	0.387	0.054
22.08.99								
6AM	0.144	0.246	0.026	7.600	0.194	0.093	0.040	0.045
4PM	0.197	0.302	0.026	7.790	0.191	0.090	0.364	0.044
23.08.99								
6AM	0.184	0.233	0.026	7.600	0.186	0.090	0.042	0.050
4PM	0.210	0.321	0.026	7.400	0.192	0.088	0.376	0.053
24.08.99								
6AM	0.169	0.240	0.026	7.400	0.192	0.095	0.042	0.048
4PM	0.185	0.315	0.026	7.400	0.200	0.088	0.376	0.078
25.08.99								
6AM	0.193	0.200	0.026	7.400	0.219	0.100	0.043	0.051
4PM	0.207	0.302	0.026	7.400	0.201	0.088	0.387	0.055
26.08.99								
6AM	0.189	0.150	0.026	7.210	0.222	0.105	0.044	0.052
4PM	0.234	0.308	0.026	7.400	0.203	0.088	0.399	0.050
27.08.99								
6AM	0.203	0.175	0.026	7.020	0.222	0.103	0.046	0.045
4PM	0.230	0.352	0.026	7.790	0.204	0.090	0.411	0.060
28.08.99								
6AM	0.192	0.258	0.026	7.020	0.225	0.100	0.047	0.053
4PM	0.228	0.333	0.026	7.790	0.206	0.090	0.423	0.064
29.08.99								
6AM	0.221	0.265	0.026	7.020	0.252	0.100	0.047	0.048
4PM	0.241	0.352	0.026	7.790	0.231	0.098	0.423	0.066
30.08.99								
6AM	0.226	0.258	0.025	6.830	0.254	0.105	0.048	0.055
4PM	0.203	0.358	0.026	7.600	0.230	0.098	0.434	0.058

Continued…..

DAY/TIME	$HCO3^{-}$	SO_4^{2-}	Cl^{-}	H_4SiO_4	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}
31.08.99								
6AM	0.225	0.200	0.026	7.210	0.251	0.108	0.047	0.054
4PM	0.231	0.377	0.026	7.600	0.225	0.095	0.423	0.050
01.09.99								
6AM	0.193	0.200	0.025	7.210	0.254	0.105	0.047	0.038
4PM	0.236	0.321	0.026	7.600	0.227	0.098	0.423	0.064
02.09.99								
6AM	0.156	0.219	0.026	7.210	0.255	0.110	0.050	0.044
4PM	0.251	0.302	0.026	7.400	0.228	0.098	0.446	0.050
03.09.99								
6AM	0.202	0.194	0.026	7.600	0.257	0.108	0.048	0.036
4PM	0.244	0.327	0.026	7.600	0.224	0.105	0.434	0.058
04.09.99								
6AM	0.197	0.213	0.026	7.600	0.260	0.105	0.047	0.053
4PM	0.239	0.290	0.026	7.600	0.222	0.103	0.423	0.055
05.09.99								
6AM	0.202	0.014	0.025	7.749	0.286	0.138	0.054	0.044
4PM	0.228	0.346	0.026	7.790	0.221	0.100	0.423	0.065
06.09.99								
6AM	0.203	0.225	0.026	7.790	0.260	0.100	0.046	0.049
4PM	0.243	0.371	0.027	7.790	0.219	0.103	0.411	0.042
07.09.99								
6AM	0.215	0.219	0.026	7.790	0.257	0.098	0.046	0.054
4PM	0.221	0.377	0.025	7.790	0.233	0.095	0.411	0.038
08.09.99								
6AM	0.198	0.219	0.025	7.790	0.261	0.108	0.047	0.053
4PM	0.228	0.346	0.026	7.790	0.221	0.100	0.423	0.052
09.09.99								
6AM	0.203	0.225	0.026	7.790	0.260	0.100	0.046	0.053
4PM	0.243	0.371	0.027	7.790	0.219	0.103	0.411	0.052
10.09.99								
6AM	0.215	0.219	0.026	7.790	0.257	0.098	0.046	0.053
4PM	0.221	0.377	0.025	7.790	0.233	0.095	0.411	0.052

Table 5.3: Melt water characteristics of Dokriani glacier for the 2000 field season

Date	Julian	EC (uS/cm)		pH		TSM (mg/l)		HCO_3^- (ppm)		H_4SiO_4 (ppm)	
	day	a.m.	p.m.	a.m.	p.m.	a.m	p.m.	a.m.	p.m.	a.m.	p.m.
1-Jul	183	46	32	7.2	6.8	11.7	7.0	10.0	10.2	8.2	8.8
2-Jul	184	42	35	7.1	6.7	12.8	8.8	11.2	8.8	9.1	8.1
3-Jul	185	48	33	7.1	7.0	12.7	10.3	12.7	10.3	10.8	10.0
4-Jul	186	44	30	7.1	7.0	11.0	6.8	11.0	6.8	9.6	9.4
5-Jul	187	51	31	8.9	7.1	27.1	7.2	27.1	7.6	8.4	8.1
6-Jul	188	36	29	7.1	7.1	9.1	7.3	9.1	7.3	10.5	6.9
7-Jul	189	37	32	7.0	7.1	11.8	7.8	11.8	9.6	8.5	7.2
8-Jul	190	33	31	7.1	7.2	9.3	7.4	9.3	8.7	6.8	8.4
9-Jul	191	35	30	6.9	7.1	9.7	7.4	9.7	8.4	12.5	8.3
10-Jul	192	34	29	7.0	7.1	8.7	8.3	8.7	8.3	7.3	7.8
11-Jul	193	33	29	7.2	7.0	9.7	7.4	9.7	7.4	7.9	6.2
12-Jul	194	33	30	7.1	7.1	7.9	6.9	7.9	6.9	7.5	7.8
13-Jul	195	34	30	7.2	7.2	11.7	6.3	11.7	6.3	7.4	10.5
14-Jul	196	34	26	7.2	7.1	11.9	8.2	11.9	8.2	6.7	7.2
15-Jul	197	32	32	7.1	7.2	11.5	8.2	11.2	8.2	7.2	7.7
16-Jul	198	31	34	7.0	7.0	11.4	8.8	9.6	8.8	7.4	7.8
17-Jul	199	30	29	7.2	7.2	11.3	7.6	11.3	7.6	7.7	7.7
18-Jul	200	29	31	7.2	7.2	11.9	8.2	11.9	8.2	8.9	7.5
19-Jul	201	36	50	7.0	7.2	9.6	8.2	9.6	11.2	8.2	11.7
20-Jul	202	34	42	7.4	7.1	9.9	8.1	9.9	12.8	9.0	9.8
21-Jul	203	39	36	7.0	7.0	13.5	8.2	13.5	13.5	9.0	9.1
22-Jul	204	36	32	7.0	7.0	5.6	12.8	5.6	12.8	7.2	6.0
23-Jul	205	39	27	7.0	6.9	10.0	9.6	10.0	9.6	7.5	6.3
24-Jul	206	39	32	6.9	6.9	10.4	10.1	10.4	10.1	8.0	8.1
25-Jul	207	40	29	7.0	6.9	10.8	7.8	10.8	7.8	8.2	6.0
26-Jul	208	36	33	7.0	6.9	10.4	7.9	10.4	7.9	7.9	7.0
27-Jul	209	36	29	7.0	6.9	33.8	33.8	13.5	13.5	7.3	8.5
28-Jul	210	36	32	7.0	6.8	29.8	23.2	11.9	9.3	8.6	7.0
29-Jul	211	36	31	7.0	7.0	31.8	27.9	12.7	11.2	7.3	7.6
30-Jul	212	34	32	7.1	6.9	28.5	8.9	22.0	8.8	4.7	5.5
31-Jul	213	33	39	7.0	7.0	29.8	27.8	11.9	11.1	7.3	8.9
1-Aug	214	36	39	7.1	7.2	33.7	31.0	13.5	12.4	4.7	4.6
2-Aug	215	46	40	7.0	7.1	72.8	13.5	12.8	13.5	5.2	4.8
3-Aug	216	41	30	7.2	6.7	10.7	11.9	10.7	11.9	4.9	4.6
4-Aug	217	42	33	7.1	7.2	11.9	8.3	11.9	8.3	6.4	5.5
5-Aug	218	40	39	6.9	7.2	11.5	9.2	11.5	9.2	5.5	5.0
6-Aug	219	40	28	6.7	6.9	13.6	12.7	13.6	12.7	5.1	5.6
7-Aug	220	38.5	29	6.8	6.7	14.3	9.5	14.3	9.5	5.9	6.1
8-Aug	221	37	29	6.9	6.8	15.9	14.3	15.9	14.3	5.3	4.8
9-Aug	222	56	32	7.2	7.1	21.9	11.9	21.9	11.9	4.4	4.1
10-Aug	223	40	33	7.0	7.0	4.9	11.2	4.9	11.2	4.0	4.0
11-Aug	224	40	31	7.1	7.0	13.9	12.7	13.9	12.7	4.6	5.0
12-Aug	225	40	28	7.1	7.1	15.9	10.6	15.9	10.6	4.8	4.3
13-Aug	226	42	32	7.1	7.2	11.9	11.2	11.9	11.2	5.3	5.4
14-Aug	227	37	34	7.1	6.9	15.1	14.0	15.1	14.0	5.1	6.9
15-Aug	228	48	59	7.1	7.0	14.3	13.9	14.3	13.9	6.3	6.4
16-Aug	229	49	39	7.1	7.1	13.0	9.5	13.0	9.5	6.4	4.5
17-Aug	230	49	50	7.0	7.0	13.8	14.6	13.8	14.6	5.5	5.9
18-Aug	231	49	35	6.9	7.0	14.4	13.5	14.4	13.5	4.1	4.6
19-Aug	232	50	38	7.1	7.1	14.4	6.4	14.4	6.4	4.8	4.0

Continued.....

Date	Julian	EC (uS/cm)		pH		TSM (mg/l)		HCO_3^- (ppm)		H_4SiO_4 (ppm)	
	day	a.m.	p.m.	a.m.	p.m.	a.m	p.m.	a.m.	p.m.	a.m.	p.m.
20-Aug	233	47	32	7.1	7.2	15.1	6.2	15.1	6.2	4.3	3.1
21-Aug	234	32	44	7.0	7.0	9.4	9.5	9.4	9.5	3.0	4.4
22-Aug	235	49	34	7.1	7.0	14.1	10.3	14.1	10.3	5.9	4.6
23-Aug	236	49	33	7.0	7.2	14.4	8.9	14.4	9.6	4.8	4.5
24-Aug	237	49	34	7.2	6.7	14.8	8.8	14.8	8.8	4.5	4.3
25-Aug	238	74	37	6.9	7.0	27.2	103.3	27.2	10.3	4.8	4.9
26-Aug	239	47	33	7.2	7.2	13.0	11.1	13.0	11.1	6.0	4.4
27-Aug	240	40	35	7.2	7.2	13.5	15.1	13.5	15.1	5.4	3.4
28-Aug	241	33	39	7.1	7.1	13.5	10.0	13.5	10.0	5.1	4.9
29-Aug	242	40	33	7.1	7.1	11.8	7.2	11.8	7.2	4.3	4.3
30-Aug	243	45	34	7.1	6.8	11.6	7.1	13.6	10.4	5.6	5.4
31-Aug	244	46	32	7.1	7.1	13.9	8.8	12.0	12.7	6.4	5.6
1-Sep	245	50	39	7.2	7.2	14.3	8.7	12.5	9.8	8.1	6.6
2-Sep	246	48	36	7.3	7.3	13.8	9.4	10.0	11.1	8.3	9.4
3-Sep	247	41	32	7.2	7.2	14.1	9.6	10.2	9.0	7.6	6.6
4-Sep	248	46	35	7.2	7.2	13.7	9.8	12.7	11.9	8.3	4.3
5-Sep	249	44	31	7.2	7.2	13.7	11.3	7.4	5.8	8.3	6.8
6-Sep	250	43	32	7.2	7.2	14.2	11.6	11.7	9.1	9.3	5.8
7-Sep	251	40	33	7.2	7.1	14.6	10.8	10.5	13.5	5.3	4.2
8-Sep	252	43	34	7.1	7.1	13.0	9.8	11.3	8.9	5.1	5.2
9-Sep	253	47	41	7.1	7.1	17.3	8.3	12.6	10.7	5.5	5.5
10-Sep	254	52	43	7.2	7.2	16.6	7.9	13.9	10.2	6.3	5.1
11-Sep	255	53	37	7.2	7.2	17.9	8.5	11.2	8.7	7.4	7.4
12-Sep	256	48	36	7.1	7.1	14.5	8.8	10.4	8.4	7.5	7.4
13-Sep	257	32	35	6.4	7.2	13.3	9.1	4.9	6.8	7.1	7.6
14-Sep	258	45	33	7.0	7.2	12.9	9.4	11.6	8.9	4.6	6.8
15-Sep	259	45	35	7.2	7.2	14.2	10.0	10.9	10.1	7.2	5.9
16-Sep	260	44	34	7.2	7.2	13.9	10.6	10.9	9.3	7.7	5.6
17-Sep	261	43	34	7.2	6.4	15.0	10.9	10.1	4.9	8.1	7.7
18-Sep	262	43	35	7.2	6.9	15.6	10.9	10.6	10.8	8.4	5.1
19-Sep	263	43	38	7.1	7.1	17.2	10.1	9.9	9.3	7.8	4.4
20-Sep	264	46	42	7.1	7.1	15.6	9.2	11.2	9.0	7.3	5.3
21-Sep	265	49	46	7.1	7.1	14.7	8.6	11.5	12.0	6.7	5.7

Table 5.4: Meltwater characteristics of Dokriani glacier for the year 2001

Date	Julian	Air Temp		water Temp		EC (uS/cm)		pH		HCO_3^- (ppm)		Rain	Disch. (m^3/s)	
	day	a.m.	p.m.	a.m.	p.m.	a.m.	p.m.	a.m.	p.m.	a.m.	p.m.	(mm)	a.m.	p.m.
1-Jun	152	12.5	8.4		0.9		30		7.17		8.37	0.0	2.1	3.29
2-Jun	153	12.1	12.7	2.7	2.5	40	26	7.33	7.37	4.10	10.17	0.0	2.21	3.46
3-Jun	154	11.6	10.5	5.6	2.8	38	24	7.31	7.35	6.76	6.76	0.0	2.16	3.40
4-Jun	155	16.5	8.8	7.8	0.7	31	29	7.30	7.34	6.76	10.17	0.0	2.02	3.48
5-Jun	156	12.2	13.1	0.8	1.2	27	22	7.27	7.28	8.37	12.17	0.0	2.31	3.52
6-Jun	157	8.6	13.7	1.4	0.9	31	28	7.20	7.42	10.17	12.10	0.0	2.28	3.73
7-Jun	158	11.3	10	5.4	2.8	29	24	7.18	7.17	5.34	8.37	0.0	2.34	4.00
8-Jun	159	17.3	9	8.4	0.6	32	23	7.10	7.18	8.37	10.17	0.0	2.09	4.04
9-Jun	160	12.6	13.5	1	1.6	28	22	7.15	7.17	10.17	12.17	0.0	2.39	4.01
10-Jun	161	16.8	8.2	1.9	0.9	30	30	7.24	7.06	10.17	12.70	0.0	2.59	3.68
11-Jun	162	12.2	12.6	2.9	2.4	36	26	7.08	7.13	5.34	12.12	0.0	2.37	3.61
12-Jun	163	11.8	10.5	5.6	2.5	33	25	7.14	7.03	8.37	10.17	0.0	2.27	3.70
13-Jun	164	17.2	8.5	8.2	0.5	31	23	7.01	7.08	5.34	8.37	0.0	1.36	2.67
14-Jun	165	12.4	13.3	0.9	1.4	28	22	7.05	7.08	8.37	12.17	0.0	1.31	2.22
15-Jun	166	8.8	13.3	1.2	0.8	30	28	7.06	7.42	6.76	12.07	5.1	1.59	2.76
16-Jun	167	16.6	9.3	1.7	1.6	30	20	7.26	7.45	8.37	10.17	14.8	2.11	2.97
17-Jun	168	15.4	8.7	1.8	1.6	31	23	7.26	7.31	4.10	5.34	0.0	1.89	3.07
18-Jun	169	16.8	9.7	1.7	1.5	31	23	7.26	7.31	8.37	10.17	0.0	2.04	3.50
19-Jun	170	16.1	13.8	1.6	1.5	31	23	7.28	7.31	5.34	10.94	0.0	1.53	2.92
20-Jun	171	12.8	11.8	1	1.7	32	21	7.27	7.30	8.37	10.07	1.0	1.94	3.62
21-Jun	172	8.3	14	0.8	1.6	29	21	7.32	7.30	5.34	8.37	6.5	2.03	3.26
22-Jun	173	9.8	10.9	0.7	1.4	28	21	7.25	7.31	4.10	6.76	8.0	2.74	3.74
23-Jun	174	11.5	9	1.7	1.4	28	22	7.25	7.27	5.34	6.72	10.0	2.44	3.30
24-Jun	175	9.2	9.4	1.8	1.7	33	25	7.31	7.31	6.76	10.17	10.0	2.36	3.34
25-Jun	176	12.5	10.8	1.8	1.7	32	24	7.30	7.32	5.34	8.37	18.2	2.27	3.99
26-Jun	177	12	10.3	2.2	1.8	30	22	7.31	7.30	10.17	12.17	13.8	2.63	4.01
27-Jun	178	14.1	18.5	2.4	1.3	29	24	7.18	7.25	8.37	10.97	2.5	2.01	4.01
28-Jun	179	19.7	19.5	2	2.4	33	24	7.24	7.26	12.17	14.37	0.5	2.34	3.77
29-Jun	180	14.3	17.1	2.8	2.5	32	23	7.26	7.29	10.17	19.38	0.5	3.05	4.18
30-Jun	181	15.5	14.7	2.6	2.3	30	25	7.27	7.31	8.37	16.77	0.0	2.79	3.86
1-Jul	182	16.5	18.3	2.6	2.5	32	24	7.24	7.30	14.37	6.46	0.0	2.6	4.10
2-Jul	183	18	15	3.2	2.3	33	42	7.12	7.70	5.34	8.37	12.2	2.18	3.50
3-Jul	184	20	11.6	3	2.1	31	24	7.07	7.24	6.76	6.72	12.3	2.03	3.45
4-Jul	185	19.1	14	2.8	2.2	33	26	7.05	6.98	6.76	8.37	6.5	2.57	3.20
5-Jul	186	16.7	16.3	3.1	2.2	35	24	7.07	7.17	5.34	8.37	12.5	2.32	2.94
6-Jul	187	14.6	18.5	2.2	2.6	26	19	6.59	7.23	6.76	8.37	12.5	2.35	4.75
7-Jul	188	17.8	13.9	2.7	2	25	18	7.03	7.13	5.34	8.57	13.0	1.79	2.68
8-Jul	189	15.4	11.5	2.4	2.2	27	27	7.24	7.07	4.10	6.76	8.2	2.37	3.05
9-Jul	190	11.5	11.1	2	2	28	39	7.32	7.69	4.10	6.72	4.5	2.09	3.02
10-Jul	191	11	12	2.3	2.2	25	28	6.67	7.38	6.46	8.71	15.5	2.08	2.92
11-Jul	192	10.7	9.8	2.4	2.4	36	27	7.52	7.40	9.98	12.81	15.5	2.14	2.78
12-Jul	193	9.9	8.5	1.9	1.9	35	26	7.32	7.13	8.71	14.37	10.0	2.15	2.50
13-Jul	194	10.1	12.3	1.8	1.9	31	26	7.23	7.02	6.46	8.71	15.0	2.41	3.59
14-Jul	195	10.5	12.1	1.7	2.1	30	26	7.25	7.29	8.71	9.52	16.5	2.14	3.51
15-Jul	196	9.4	14.8	1.8	2.3	33	26	7.25	7.26	3.76	14.37	10.0	2.03	3.65
16-Jul	197	15.2	12.6	2.2	2.5	27	24	7.09	7.12	5.00	7.54	10.0	1.84	2.65
17-Jul	198	11.8	10.8	2.7	2.5	36	28	7.20	7.24	9.98	9.98	5.5	1.85	2.87
18-Jul	199	12.5	20.1	2.9	2.5	34	36	7.20	7.40	6.46	12.81	0.0	2.11	2.48
19-Jul	200	15	13.7	2.5	2.1	32	48	7.10	7.30	8.71	9.98	1.7	2.39	3.94
20-Jul	201	17.3	12.6	2.3	1.5	31	44	7.12	7.28	11.35	8.71	23.0	2.28	3.97

Continued…..

Date	Julian	Air Temp		water Temp		EC (uS/cm)		pH		HCO_3^- (ppm)		Rain	Disch. (m^3/s)	
	day	a.m.	p.m.	a.m.	p.m.	a.m.	p.m.	a.m.	p.m.	a.m.	p.m.	(mm)	a.m.	p.m.
21-Jul	202	15.2	13.1	2.2	2.2	33	39	7.06	7.32	7.54	11.35	9.5	3.33	3.72
22-Jul	203	13.3	13	2.6	2.4	34	39	7.11	7.34	6.46	12.81	60.0	2.02	3.35
23-Jul	204	10.1	18.1	2.4	2.6	28	36	7.20	7.48	9.98	11.30	7.5	2.02	4.96
24-Jul	205	13.2	13.1	2.6	2.6	26	32	7.02	7.12	11.35	7.54	0.5	2.11	3.76
25-Jul	206	14.1	15.3	2.9	2.6	25	29	7.04	7.20	9.92	10.17	0.5	2.26	3.57
26-Jul	207	14.2	15.2	2.5	2.8	30	38	7.28	7.42	6.46	8.37	16.5	2.24	3.30
27-Jul	208	15.4	17.2	2.5	2.7	30	15	7.48	6.89	6.46	10.17	3.5	2.01	4.18
28-Jul	209	21.4	16	2.4	2.4	23	24	7.18	7.14	10.17	10.17	1.5	1.75	4.31
29-Jul	210	17.1	14.5	2.3	2.2	32	21	7.22	7.02	8.37	10.47	2.5	2.01	3.15
30-Jul	211	18.8	12	2.2	2.1	28	21	7.46	7.28	4.10	10.10	1.5	2.29	3.10
31-Jul	212	13.4	12.8	2.4	2.5	29	20	7.22	7.80	6.76	12.17	0.0	2.27	2.95
1-Aug	213	14.6	11.7	2.2	1.8	29	17	7.90	7.82	8.37	12.10	0.0	2.15	4.18
2-Aug	214	18.8	10.6	2.7	1.6	28	19	7.48	7.60	10.17	12.17	0.0	2.09	3.77
3-Aug	215	14.1	11.3	2.4	2.1	26	21	7.32	7.54	8.37	10.17	0.0	2.1	3.72
4-Aug	216	15.2	15.4	2.2	2	32	34	7.08	7.28	8.37	12.42	0.0	2.74	3.50
5-Aug	217	15.6	16.8	2.4	2.3	31	35	7.02	7.32	8.37	8.37	0.0	2.45	3.48
10-Aug	218	10.8	15.5	2.5	2.2	37	30	6.89	7.01	5.34	6.76	11.0	2.18	3.20
11-Aug	219	14.3	17.2	2.5	2.1	40.5	43.5	7.07	7.26	5.96	7.12	0.0	2.43	4.12

main source of chloride in the ecosystem. Besides, the evaporite bedrock basin contributes to the concentration of chloride in water. The average concentration of chloride in the meltwater of the year 1999 was 0.025 meq/l. Chloride concentration was almost constant throughout the season, which is quite evident from the standard deviation value of the order of 0.002 meq/l. The small variations had also been reported during 1992-1995 ablation seasons. (Hasnain, 1995)

Dissolved Silica: The most important source of silica in the meltwater is the weathering of silicate minerals (Berner, 1984; Davis, 1986; James and Jorg, 1991). The average concentration of silica in the meltwater during ablation seasons 1999 and 2000 was 8.0ppm and 6.5ppm respectively. Silica concentrations decrease as the rainfall-induced increase in discharge gives less time for the sediments to interact with the meltwater. It has been observed (Fig. 5.2) that silica and HCO_3^- follow almost inverse relationship for the ablation season 2000. Simillar trend for silica has been observed for the year 2001 (Fig. 5.3)

Cations: The analysis of meltwater samples revealed Ca^{2+} dominance among cations, followed by Na^+, Mg^{2+}, and K^+. The average ionic concentration of Ca^{2+}, Na^+, Mg^{2+} and K^+ in 1999 was 0.258 meq/l, 0.172 meq/l, 0.092 meq/l, and 0.045 meq/l respectively and showed monthly variations. The concentrations of most of the ions were found to be more in the monsoonal months of July and August.

5.5 SOLUTE ACQUISITION BY GLACIAL MELTWATER

The chemical composition of meltwater has demonstrated high rate of chemical weathering in sub-glacial environment (Reynold and Johnson, 1972; Collins, 1979; Raiswell, 1984; Sharp et al., 1995; Brown, 1996). Weathering of rock forming minerals and atmospheric precipitation are the major sources of solute content of melt water. Therefore chemical composition of the meltwater in terms of dissolved ions can be explained on the basis of various rocks present in the glacier basin (Gorham, 1961; Meyback, 1983). The two major anions, HCO_3^- and SO_4^{2-}, in the glacial meltwater

Fig. 5.1: Pattern of SO_4^{-2} and HCO_3 in the meltwaterduring the ablation season 1999

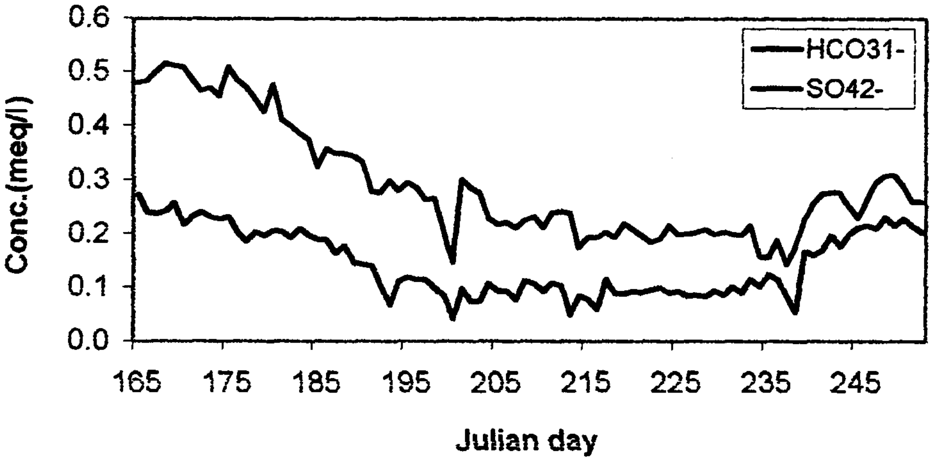


Fig. 5.2: Pattern of HCO_3^- and Silica in the meltwater during the ablation season 2000

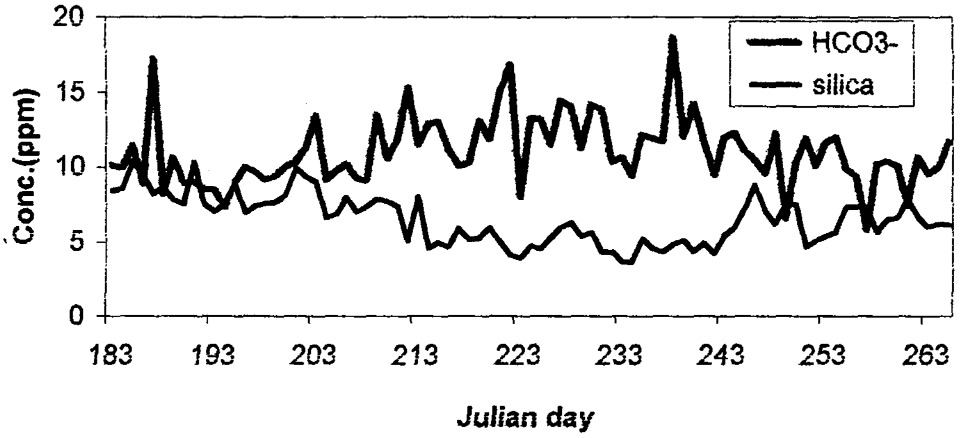
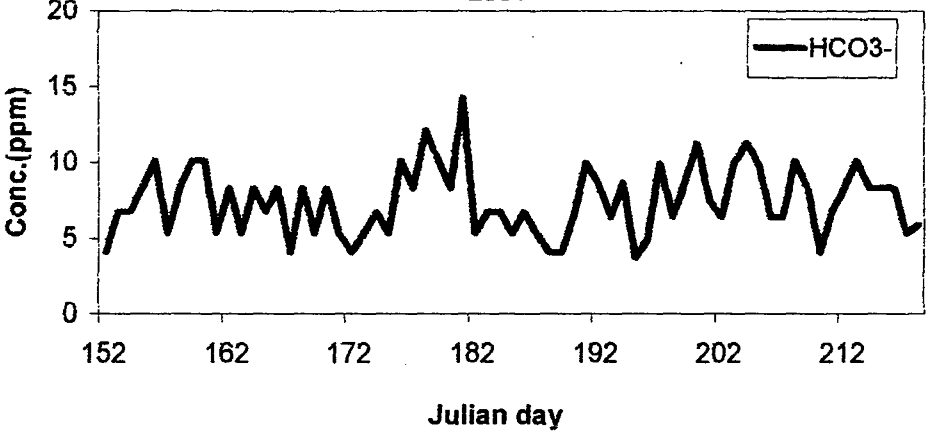


Fig. 5.3: Pattern of HCO_3^- in meltwater during the ablation season 2001



are mainly derived from the dissolution of atmospheric carbon dioxide and carbonates and the oxidation of pyrites (Souchez and Lemmens, 1987). Dissociation of CO_2 and sulphide oxidation is the two main reactions that provide the bulk of the protons to weather carbonates, silicates and aluminosilicates in the drainage basin. The anionic content therefore, reflects the acidic sources used in the chemical weathering of bedrock minerals. The relative proportion of various ions in solution depends on their relative abundance in the bedrock and their solubility (Raiswell, 1984; Tranter et al., 1993). Diurnal variations in water chemistry of meltwater can be explained by the two-component flow of meltwater, suggested by Rainwater and Guy (1961) and Collins (1979). In the first component, the sub-glacial water gets enriched with dissolved solids because of long residence time and contact with bed sediment. In contrast to this, the second component, the supraglacial meltwater is less enriched with ionic species, flows fast and flow is directly controlled by heat flux. Variable dilution of concentrated subglacial water by diluted supraglacial water causes variations in the chemistry of glacial fed streams.

The sources of dissolved ions in meltwater of Dokriani glacier have been evaluated by studying the correlation matrix for the ions. The correlation matrix for ions during the ablation season of 1999 (Table 5.5) shows that HCO_3^- is highly correlated with Ca^{2+} (R^2=75%) and SO_4^{2-} with Silica (R^2=76%). The proportion of HCO_3^- and SO_4^{2-} in the meltwater reflects the relative dominance of the two major sources of protons during subglacial chemical erosion. According to Brown et al. (1996) the ratio of HCO_3^- to (HCO_3^- + SO_4^{2-}) referred as C-ratio having a value of 1.0 when carbonation reactions, involving atmospheric CO_2 dominates as given in the following reaction.

Table 5.5: Correlation matrix for major ions

	HCO_3^-	SO_4^{2-}	Cl^-	H_4SiO_4	Ca^{2+}	Mg^{2+}	Na^+	K^+
HCO_3^-	1							
SO_4^{2-}	**0.72**	1						
Cl^-	-0.08	-0.19	1					
H_4SiO_4	0.47	**0.76**	-0.14	1				
Ca^{2+}	**0.75**	0.49	-0.08	0.25	1			
Mg^{2+}	0.35	-0.13	0.03	-0.25	**0.6**	1		
Na^+	0.37	0.39	0.18	0.34	0.12	-0.1	1	
K^+	0.43	0.11	0.17	-0.08	0.34	0.41	0.3	1

$CaCO_3$ (s) + CO_2 (aq) + H_2O (aq) = Ca^{2+} + HCO_3^- (aq) ....(1)

$CaAl_2Si_2O_8$ (s) + $2CO_2$ (aq) + $2H_2O$ (aq) = Ca^{2+} (aq) + $2HCO_3^-$ + $H_2Al_2Si_2O_8$ (s) ....(2)

If the C-ratio is 0.5, it means coupled reaction involving the weathering of carbonates by proton derived from oxidation of sulphides

$4FeS_2$ (s) + $16CaCO_3$ (s) + $15O_2$ (aq) + $14H_2O$ (aq) = $16Ca^{2+}$ (aq) + $16HCO_3^-$ (aq) + $8SO_4^{2-}$ (aq) + $4Fe(OH)_3$ (s) ....(3)

The C-ratio for the Dokriani glacier meltwater has been divided into three parts. During the month of June the C-ratio has been found to be 0.69, which indicates that during this period, evolution of ions in the meltwater was promoted by the coupled reaction involving the weathering of carbonates by protons derived from sulphide oxidation. The C-ratio increases during monsoonal months of July and August-September to the values of 0.81 and 0.88 respectively. In these monsoonal months, water from snow and icemelt passes through the hydrological system rapidly, resulting in increased discharge. The increase in C-ratio during monsoonal months indicates that additional protons were derived from the dissolution and dissociation of atmospheric CO_2 (Brown et al., 1996). During monsoon season, cloud cover over the entire Garhwal Himalaya cuts off radiation falling on the surface of the glacier and causes snowfall in the accumulation zone and rainfall in ablation zone (Collins and Hasnain, 1995). Meltwater discharges during this period are likely to be sustained by drainage of a sub-glacial reservoir built over the previous months. Hence the runoff contains a very high proportion of stored subglacial water. The average C-ratio for the ablation season 1999 has been computed as 0.77, suggesting the involvement of coupled reactions involving the carbonate weathering by protons derived from the oxidation of sulphide in controlling the meltwater composition (Fig. 5.4).

The rate and manner of release of chemical constituents from atmospheric and

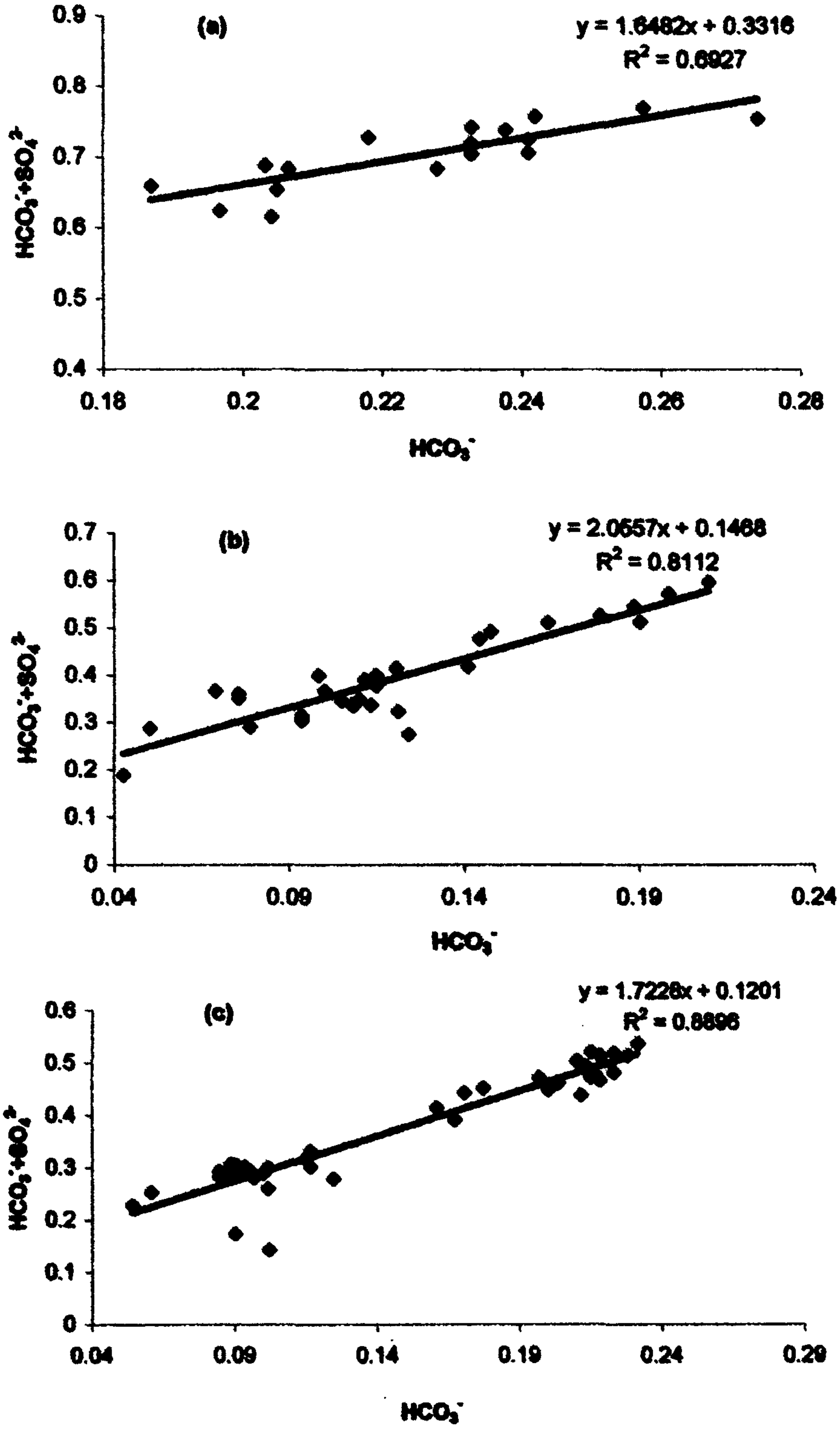


Fig. 5.4: Scatter plot between $HCO_3^-+SO_4^{2-}$ and HCO_3^- for the month of (a) June (b) July (c) August- September

lithospheric sources in alpine environment is largely controlled by snow/ice (Collins, 1981) and regolith storage reservoirs (Zeman and Slaymaker, 1975). In general biospheric sources are not explicitly considered since inputs are assumed to approximate outputs, and constituents exhibit a significant flow dilution relationship i.e. concentration decreases as discharge increases (Stednick, 1989). This is attributed to the dilution factor.

The hydrochemical characteristic of meltwater draining from glaciated environment is different from the other aqueous ecosystem, due to its mountainous nature and extreme cold climatic conditions. The high concentration of various chemical constituents in meltwater shows the intense chemical weathering in the basin. Among physical weathering grinding action of the glacier has a strong bearing on the chemistry of meltwater (Slouches and Lemmens, 1987). Reynold and Johnson (1972) have demonstrated that the silicate minerals are capable of reacting fairly rapidly with water at near freezing point. The low temperatures and eddies in the meltwater draining from the glacier encourage the dissolution of atmospheric carbon dioxide in water. The carbon dioxide reacts with water and forms weak acid and enhances the supply of hydrogen ions needed for the chemical hydrolysis of minerals. This give rise to bicarbonates, cations, dissolved silica and clay minerals (Raiswell, 1984). Partial dissolution of suspended particle may also contribute substantially to the solute concentration (Collins, 1979; Brown et al., 1994). Hydrochemical investigation in glacier basin can be inferred in terms of chemical characteristics of meltwater and variation in the concentration of suspended sediments and dissolved solids in temporal and spatial scale, to assess the dynamics, which control and operate in the glacio-fluvial regime. Various studies on the Alps and Himalayan glaciers by (Rainwater and Guy, 1961; Behrens et al., 1971; Lorrain, 1972; Collins 1979 a; 1979 b; Hasnain, 1992, 1995, 1996, 1999) have suggested two principal flow components. (1) water passing through subglacial channels having long residence period and (2) Supraglacial water, which is fast flowing and largely controlled by heat flux.

The chemical composition of Dokriani glacier meltwater showed 39% Ca^{2+} out of the total cations followed by Na^+ 37%, Mg^{2+} 16% and K^+ 8% (Fig. 5.5) for the ablation season 1999. Therefore the cationic concentration in meltwater was in the order $Ca^{2+} > Na^+ > Mg^{2+} > K^+$.

Dominance of Ca^{2+} in the meltwater implies that $CaCO_3$ dissolution is the main process of solute acquisition. The dissolution of calcite proceeds more vigorously than silicate breakdown (Raiswell, 1984; Raju, 1993; Pandey, 1999). In the meltwater, Ca^{2+} is the most dominant cation and about 97% of the global runoff contains Ca^{2+} and Mg^{2+} as ionic species (Meyback, 1981). According to Collins (1979 a, 1979 b) and Thomas (1984), the dominance of Ca^{2+} in meltwater is a common phenomenon and has been reported almost everywhere. Cationic composition of Dokriani glacier meltwater in comparison to other glaciers is shown in (Table 5.6). In the present study $Ca^{2+}+Mg^{2+}$ together constitute 55% of the total cations. The high contribution of $Ca^{2+}+Mg^{2+}$ to the total cations, high $(Ca^{2+}+Mg^{2+})/(Na^++K^+)$ ratio and low $(Na^++K^+)/TZ^+$ ratio (Fig.5.6) indicates that the carbonate weathering could be a major source of dissolved ions in the meltwater. By plotting (Na^++K^+) vs. TZ^+ contribution via silicate weathering can be taken into account. The $(Na^++K^+)/TZ^+$ ratio for the Dokriani glacier is 0.57 which indicates, contribution of silicate weathering. The value of $R^2=0.57$ for $(Na^++K^+)/TZ^+$ is less than that for $(Ca^{2+}+Mg^{2+})/TZ^+$ which is $R^2=0.85$.

Relationship of (HCO_3^- and SO_4^{-2}) to total cations (TZ^+) for ablation season 1999 has been shown in Fig 5.7 and 5.8. Compared to SO_4^{-2} ($R^2 = 0.17$), HCO_3^- has shown significant correlation with TZ^+ ($R^2 = 0.43$). Relationships between HCO_3^- and (Ca^{2+} + Mg^{2+}) has been shown in Fig. 5.9. HCO_3^- has shown good correlation with ($Ca^{2+}+Mg^{2+}$) in monsoon season particularly in late monsoonal months of August-September ($R^2=0.75$) rather than pre-monsoon month of June ($R^2=0.52$). The correlation of HCO_3^- with ($Ca^{2+}+Mg^{2+}$) indicates that these ionic species have common source of their release into the meltwater i.e by weathering of carbonate rocks. Ca^{2+}

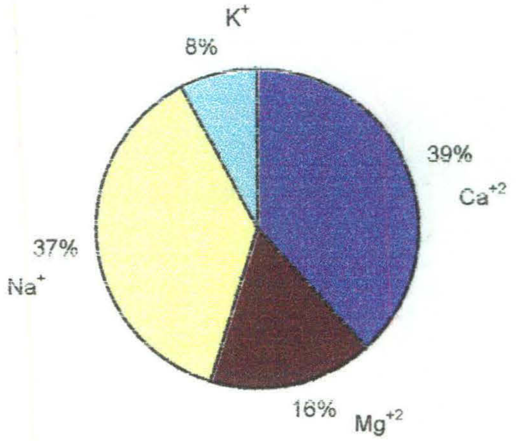


Fig.5.5: Proportion of cations and anions in meltwater

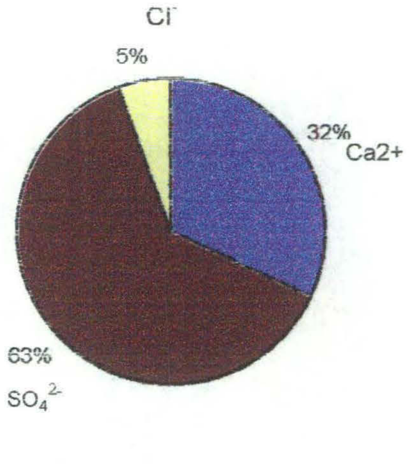


Table 5.6: Cationic composition of Dokriani glacier meltwater in comparison to other glaciers

Glaciers	Year	No. of Samples	Range as % (Ca^{2+}+ Mg^{2+} + Na^{+} +K^{+})				Reference
			Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	
Dokriani Glacier							
Aug-Sep	1992	188	45-70	28-Mar	18-Jun	18-Aug	Hasnain (1999)
Oct-Nov	1993	88	39-75	21-Sep	18-Jun	21-Aug	Hasnain (1999)
May-Oct	1994	360	66-90	15-Mar	15-Sep	23-Jul	Hasnain (1999)
Jun-Sep	1999	345	29-56	13-26	14-Dec	9-May	**Present study**
Gornergletscher							
Jul-Aug	1974	69	45-90	5.2-23.3	1.3-17.4	1.8-22	Collins (1979)
Jul-Sep	1975	59	57-73.1	14-18	1.9-8.8	9.6-26.5	Collins (1979)
Jul-Aug	1976	41	52.7-76.1	13.5-17.6	3.2-8.1	3.9-25	Collins (1979)
Lewis glacier							
Jun-Aug	1974	14	38.1-39.7	7.5-11	44.6-47	4.7-12	Church (1974)

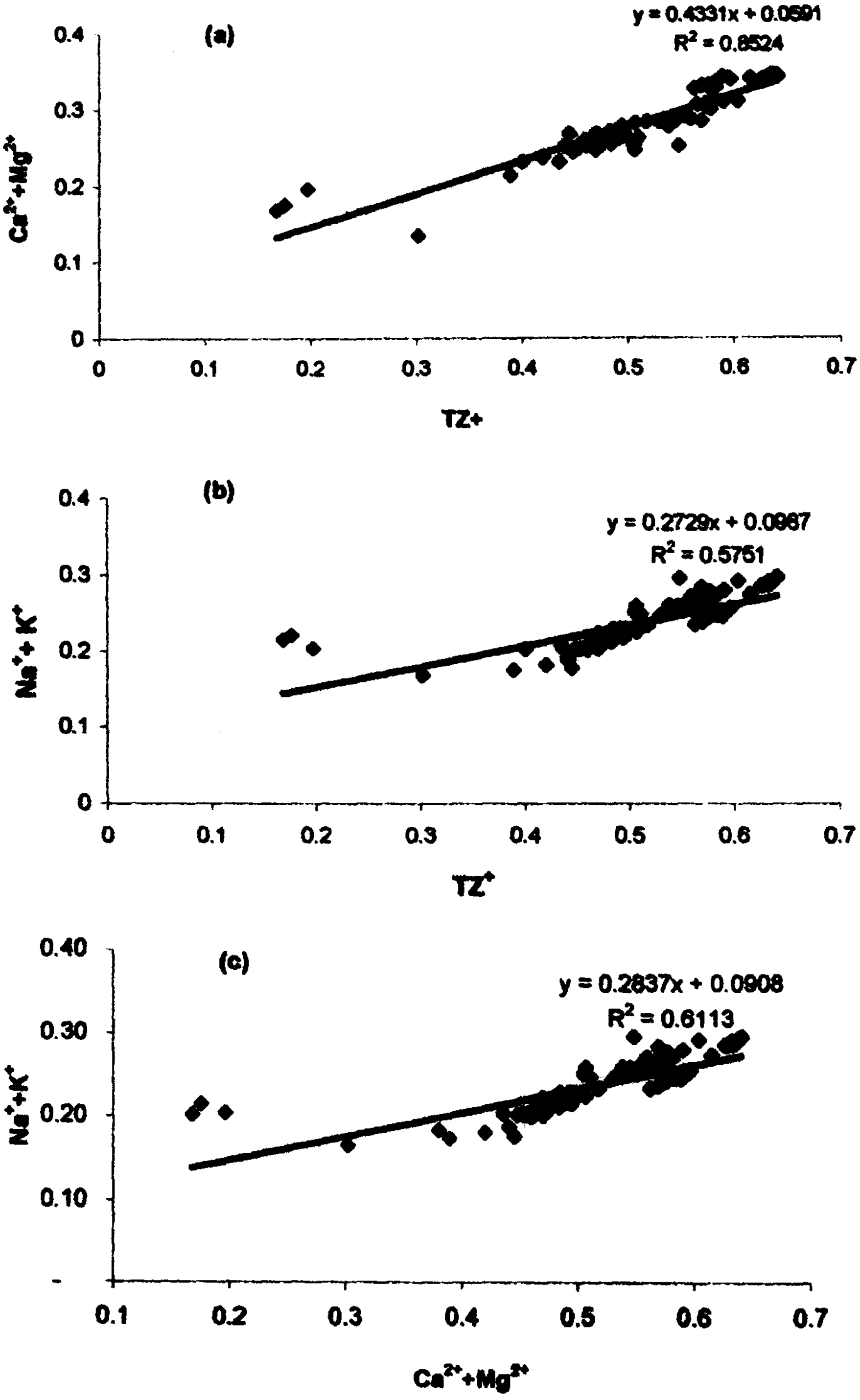


Fig. 5.6: Scatter plot for (a)(Ca^{2+}+Mg^{2+}+ vs. TZ^{+}) (b) (Na^{+}+ K^{+} vs.TZ+) (c) (Na^{+}+ K^{+} vs. Ca^{2+}+ Mg^{2+}) for the ablation season 1999

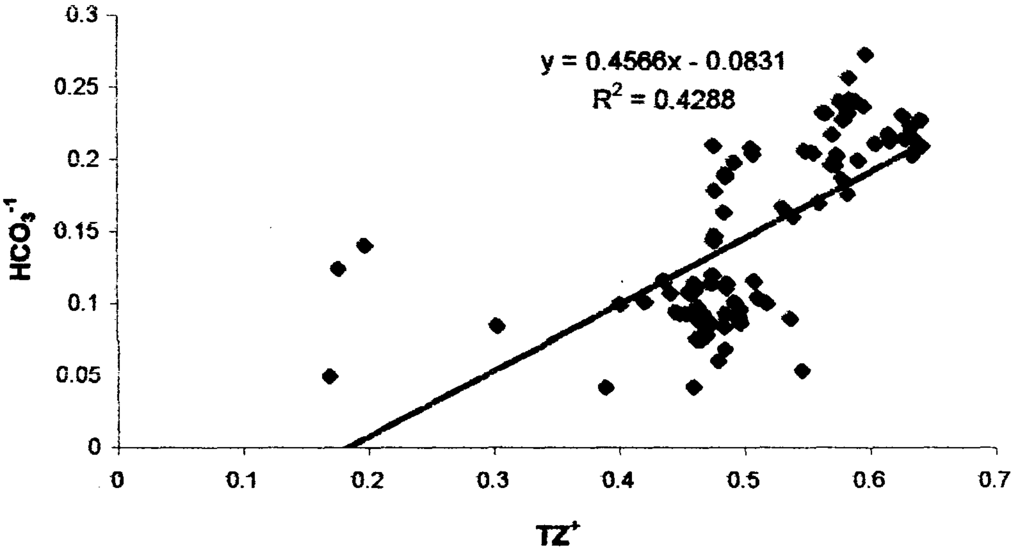


Fig. 5.7: Scatter plot between HCO_3^- and TZ^+

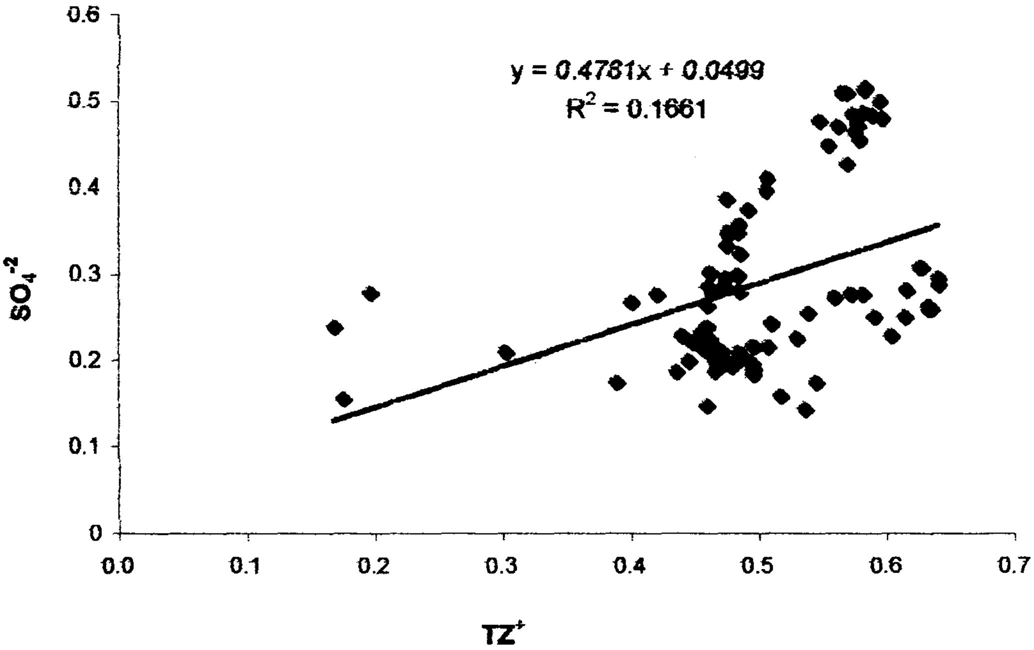


Fig. 5.8: Scatter plot between SO_4^{2-} and TZ^+

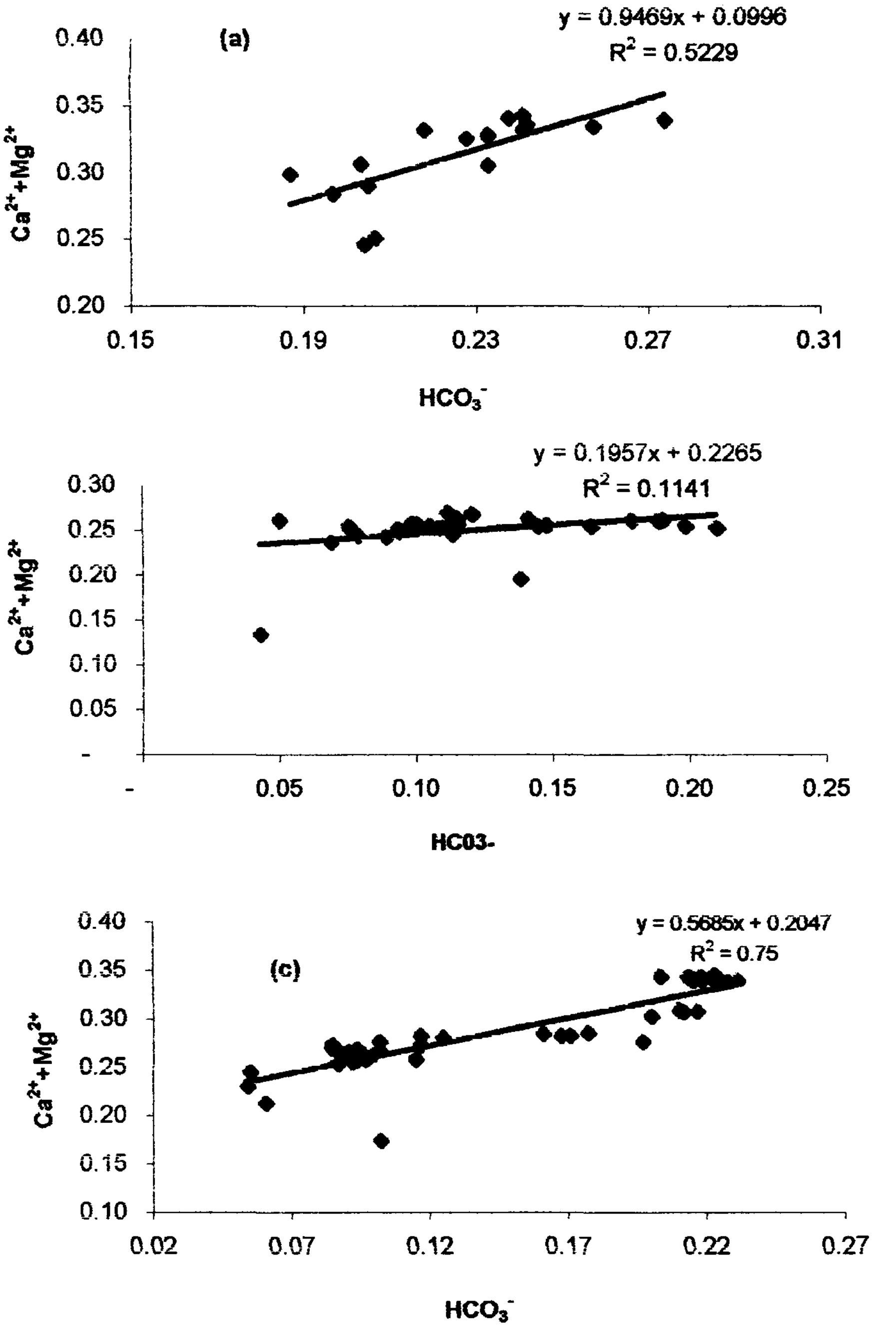


Fig.5.9: $Ca^{2+}+Mg^{2+}$ vs. HCO_3^- for the month of (a) June (b) July (c) August- September, 1999

and Mg^{2+} themselves also reveal significant correlation of the value of $R^2=0.60$, which again indicates that the presence of Ca^{2+} and Mg^{2+} in meltwater is the weathering of carbonates rocks dominated by calcium and magnesium.

Monsoonal rainfall plays a significant role on weathering of minerals and hence evolution of ionic contents in meltwater. The total amount of rainfall recorded during the 1999 ablation season was 630mm, mostly during the months of July and August. The rainfall pushes large quantities of debris into the glacier sole through crevasses (Hasnain and Chauhan, 1993). Successive diurnal melting of snow and ice rapidly leaches most of sulphate from the snow and ice (Davies et al., 1982). Hence later in the ablation season, the leached snow and ice give rise to sulphate depleted supraglacial meltwater (Tranter and Raiswell, 1991). The release of sulphate by the oxidation of sulphides in suspended sediment is a slow process and therefore is only likely to contribute significant sulphate concentrations to water, which have spent long periods at the glacial bed in contact with sediments (Brown et al., 1994). Contrary to these observations, Dokriani glacier meltwater revealed high sulphate concentrations even during monsoonal months of July, August and September. This may be due to the fact that continued low intensity rainfall may have initiated pyrite oxidation within the supraglacial moraines. Occasional high intensity rainfall may leach the sulphate from the debris and cause its domination during the seasonal high flow period of July and August, when suspensded sediment concentrations are high.

5.6 DIURNAL AND SEASONAL VARIATION IN IONIC CONTENT OF MELTWATER

Marked diurnal and seasonal variations have been found in chemical composition of meltwater. In general, ionic concentrations are high in the morning, decrease in the noon followed by increasing trend in the late evening. According to Rainwater and Guy (1961) and Collins (1983) in the afternoon with an increase in insolation, englacial channels become active and a large amount of supraglacial meltwater is available for transportation in proglacial stream. Supraglacial water derived from the surface flow through the glacier without delay and without chemical enrichment, causes dilution of the solute concentration. In the morning and late evening low supply of solar energy reduce the melting and dilution of subglacial water. The subglacial water is produced at the sole due to pressure melting and has higher ionic concentration as a result of higher residence time and longer contact with solute rich base. The dissolved load also revealed significant seasonal variations. The concentrations of most of the ions were found to be more during active monsoon season usually in the month of July and August. Variable dilution of solute rich subglacial flow from ground environment by dilute surface meltwater causes the fluctuation in solute concentration of meltwater emerging out from glacier (Rainwater and Guy, 1961). The change in the development of subglacial hydrologic network has been considered to be the most important factor leading to the variations in the delivery of ions to the meltwater stream (Collins, 1981, 1983; Hasnain et al., 2001). Since the subglacial channels are slow, the water gets enriched in solutes, as it traverses through these channels.

Based on the chemical analysis of meltwater chemical denudation rate for the one water cycle can be calculated. For this to achieve, it is necessary to have mean monthly denudation rate. For Dokriani glacier Hasnain and Thayyen (1994), calculated the chemical denudation rate of the value of 254.4 tons/km^2/yr (Table 5.8), which is seven times higher than the global average chemical denudation rate (36 tons/km^2/ yr.). Similarly by calculating mean suspended sediment flux for each month the rate of physical erosion can be ascertained. Mean monthly solute load and total chemical denudation rate of Dokriani glacier basin for the ablation season 1999 have been shown in Table 5.7 and 5.8. The high rates of chemical and physical denudation are probably due to high relief, heavy rainfall, glacial erosion, and favourable lithology that contribute to the intense weathering in the Himalaya.

Table 5.7: Solute load in Dokriani glacier meltwater, 1999

Months	Solute flux (tons/ km2/ yr)	Solute flux (%)
June	9.3	5
July	59	26
August	91.2	58
September	31.5	11

Table 5.8: Chemical denudation rates of few glacier basins

Glacier and River basin	Denudation rate (tons/km^2/yr)	Sources
European glaciers (Swiss Alps)		
Haut Glacier d, Arolla	39	Sharp and others (1995)
Glacier de Tsijiore Nouve	3	Souches and Lemmens (1987)
Gornergletscher	28	Collins (1983)
Gornergletscher	61.7 ± 30	Metcalf (1986)
North American Glaciers		
Northern cascade glacier	57	Reynold and Johnson (1972)
Berendon Glacier	58	Eyle and others (1982)
Himalayan glaciers		
Dokriani glacier (1994)	254.4	Hasnain and Thayyen (1999)
Dokriani glacier	191	**Present study**

To find out the diurnal variations in ionic contents of meltwater hourly sampling were carried out after an interval of every 15 days. The samples collected were analysed for the determination of concentration of HCO_3^- and SO_4^{2-} and discharge measurements were also carried out simultaneously. In the ablation season of 1999, hourly samples were collected on 13 July, 30 July, 15 August, and 30 August. The diurnal variations of discharges have been plotted against EC (Fig. 5.10 to 5.13). Similarly hourly samples were collected on 15 July, 30 July, 15 August and 30 August in the ablation season 2000 and 2001. The relationship between discharge and EC for these selected dates have been shown in (Fig 5.14 to 5.17) and (Fig 5.18 to 5.21). It has been found that discharge and EC follow inverse relationship. The EC exhibited high values in the morning, decreases at noon followed by increase in the evening. In the noon due to high insolation, dilution factor is more, which is accompanied by more discharge and low values of EC. As the day progresses towards evening the discharge decreases due to decrease in insolation.

Diurnal changes in discharge and solute flux have also been studies for ablation season 1999. To find out diurnal variations hourly sampling were done for establishing the relationship between the two (Fig. 5.22 to 5.25). It has been observed discharge and solute flux follow inverse relationship and diurnal change in discharge is more pronounced than change in solute flux (Lewis and Grant, 1979). Similar trend in seasonal discharge and EC (Fig. 5.26 to 5.28) for ablation season 1999, 2000 and 2001 have been observed.

5.7 SUSPENDED SEDIMENT CONCENTRATION (SSC) IN DOKRIANI GLACIER MELTWATER

Several investigators have discussed sediment transport in the glacierised basins in different parts of the world. Repp (1988) and Bogen (1999) have studied suspended sediment transport in the northwest Svalbard area of Arctic region. Gurnell et al.

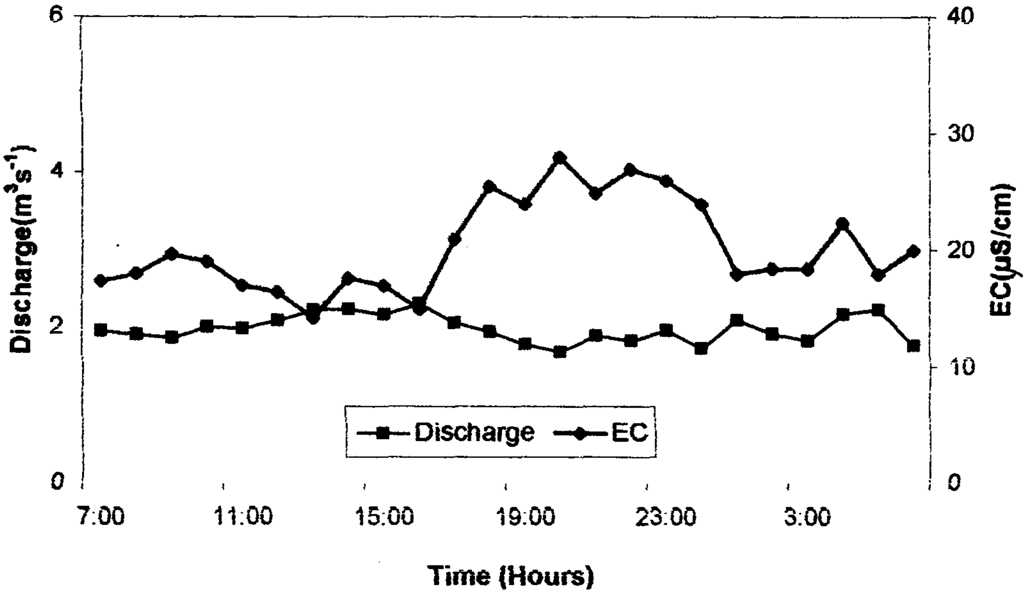


Fig.5.10: Relationship between EC and discharge for hourly experiment conducted on July 13-14,1999

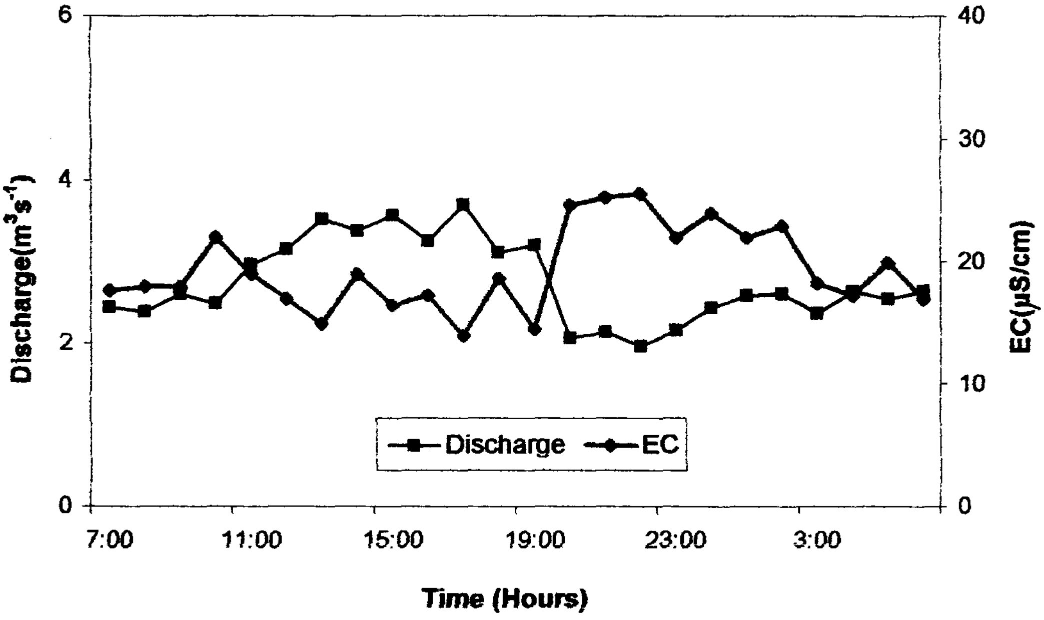


Fig. 5.11: Relationship between EC and discharge for hourly experiment conducted on July 30-31, 1999

Fig. 5.12: Relationship between EC and dishcarge for hourly experiment conducted on August 15-16, 1999

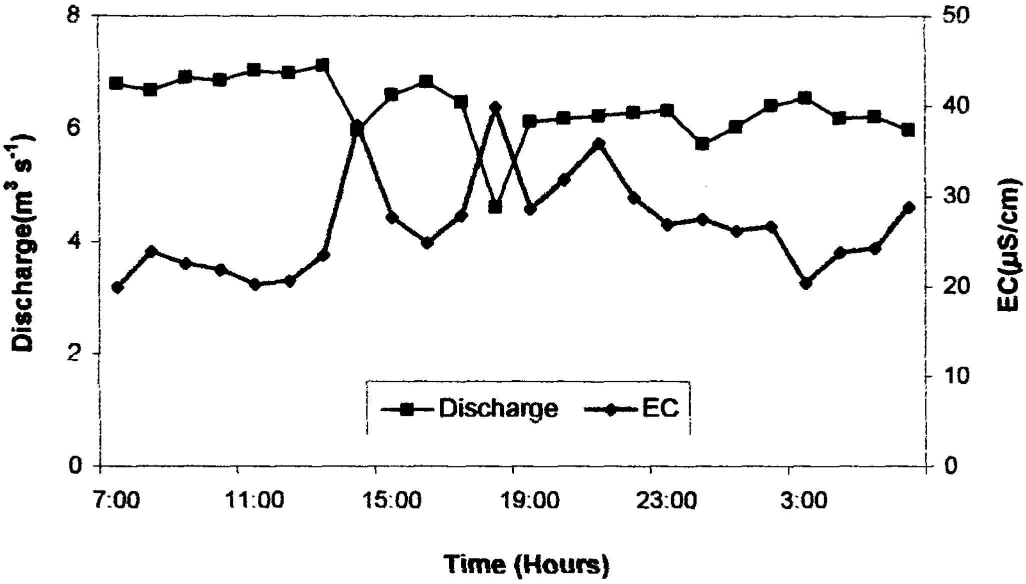


Fig. 5.13: Relationship between EC and discharge for hourly experiment conducted on August 30-31, 1999

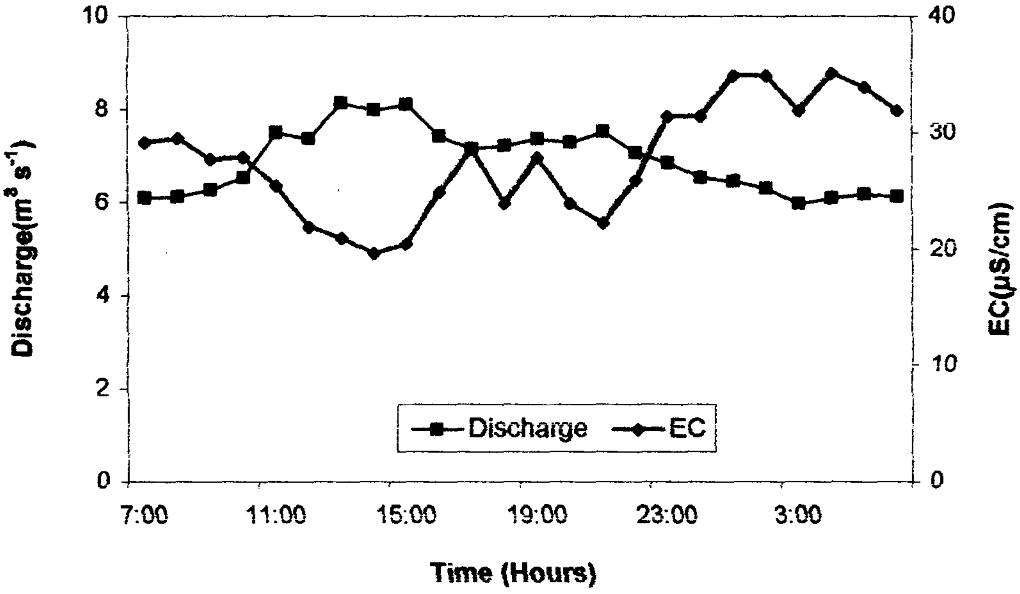


Fig. 5.14:Relationship between EC and discharge for hourly experiment conducted on July 13-14, 2000

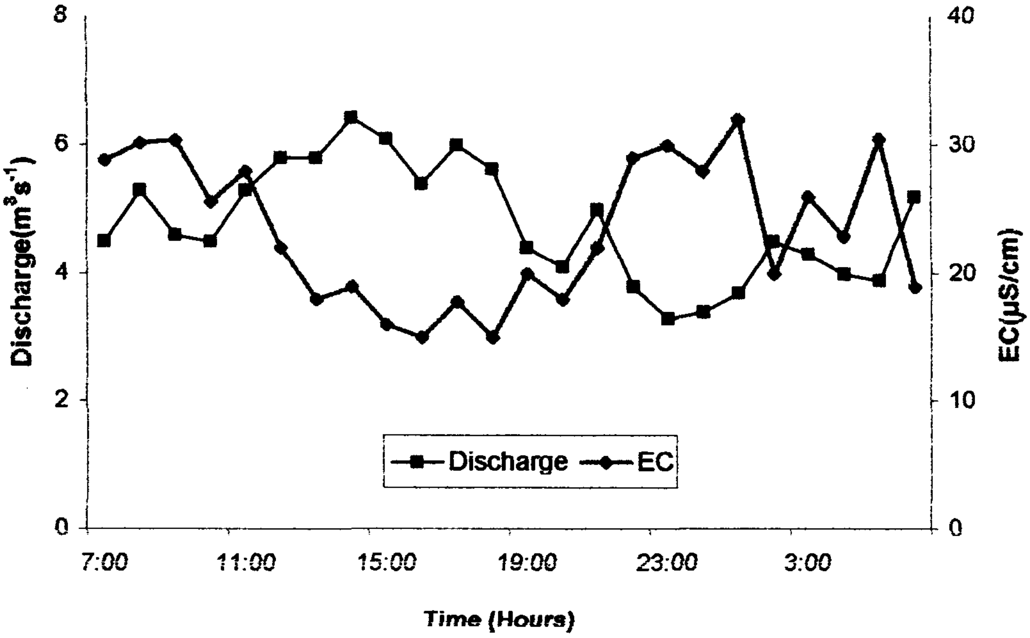


Fig. 5.15: Relationship between EC and discharge for hourly experiment conducted on July 30-31, 2000

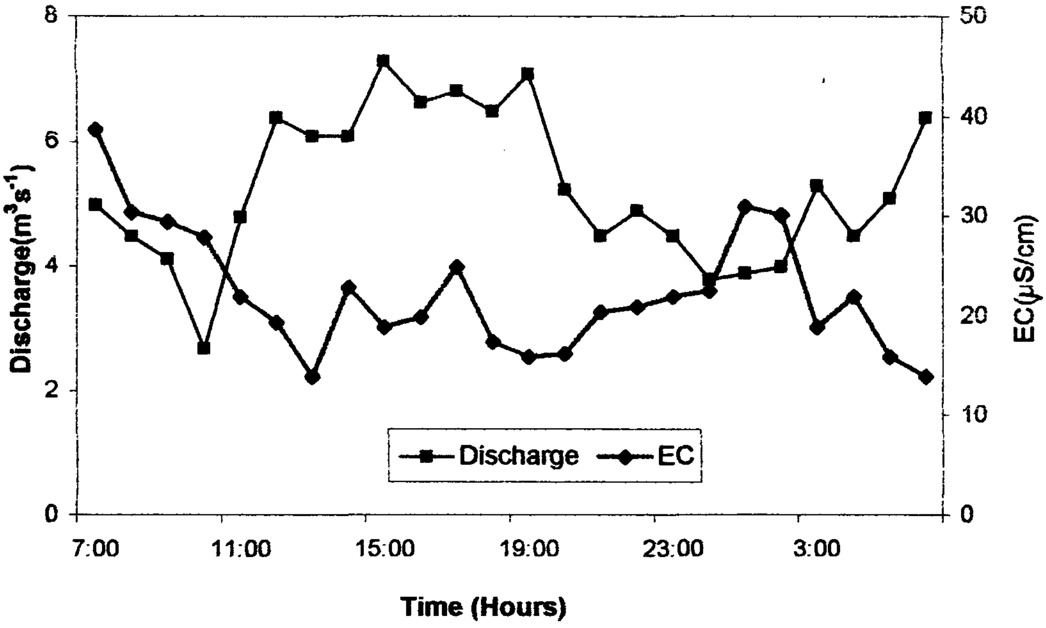


Fig. 5.16: Relationship between EC and dishcarge for hourly experiment conducted on August 15-16, 2000

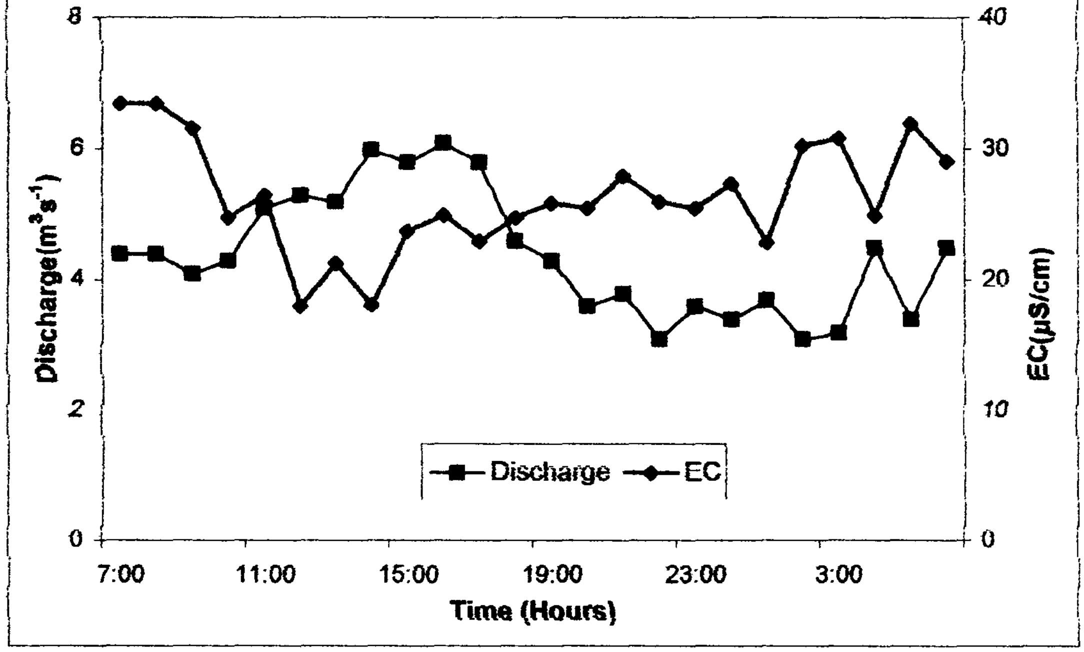
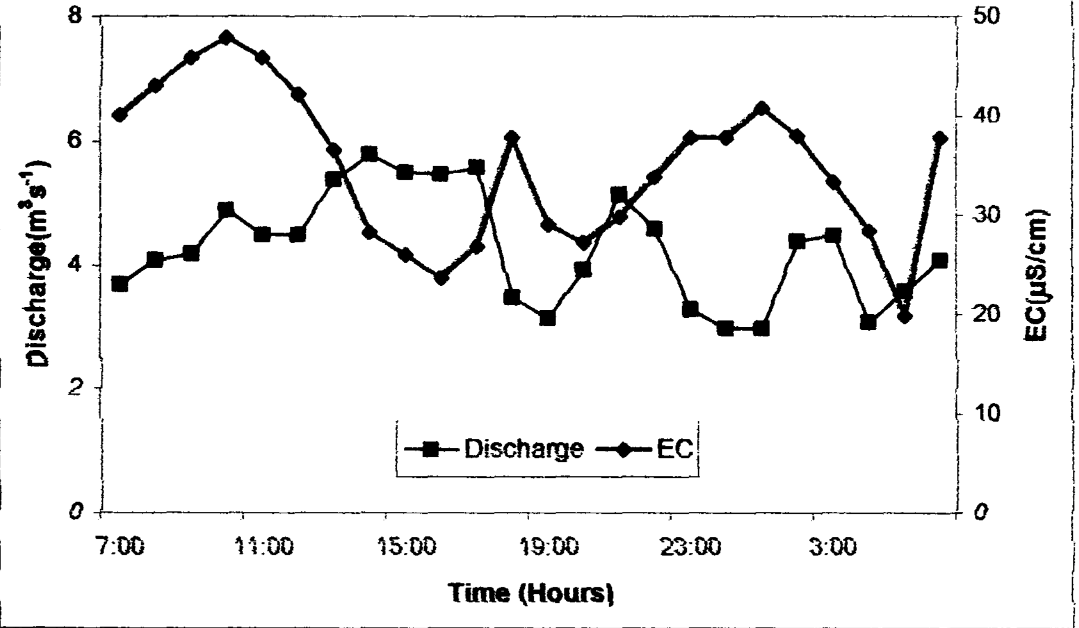


Fig. 5.17:Relationship between EC and discharge for hourly experiment conducted on August 30-31, 2000



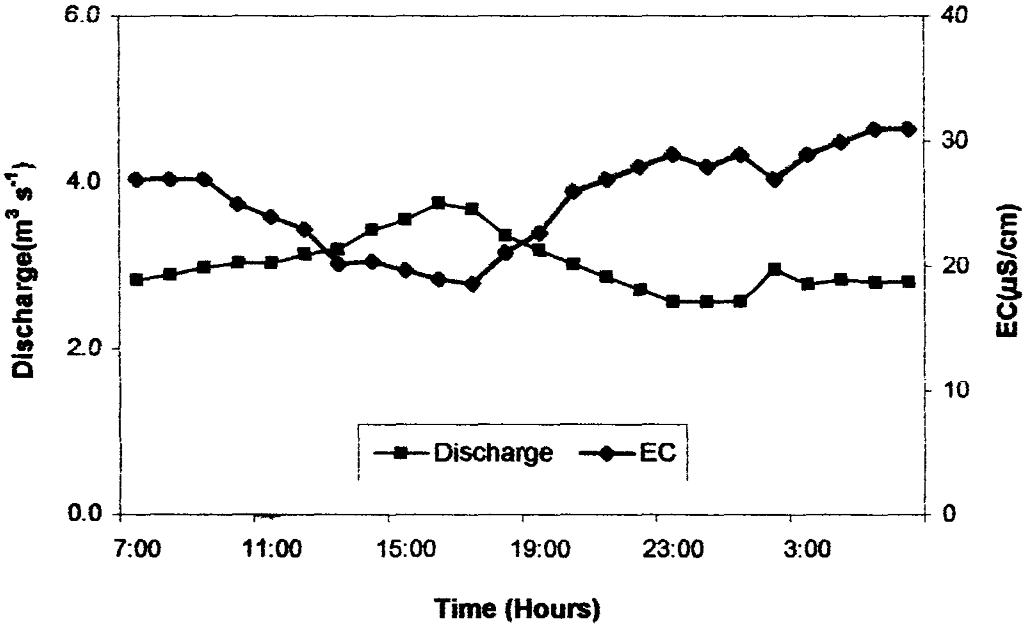


Fig.5.18:Relationship between EC and discharge for hourly experiment conducted on July 13-14, 2001

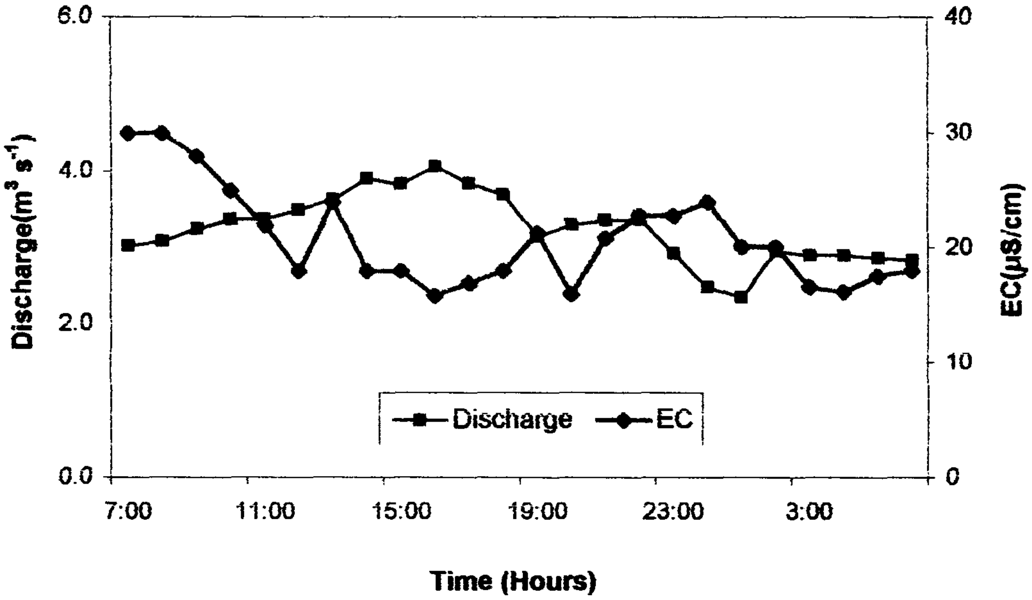


Fig. 5.19:Relationship between EC and discharge for hourly experiment conducted on July 30-31, 2001

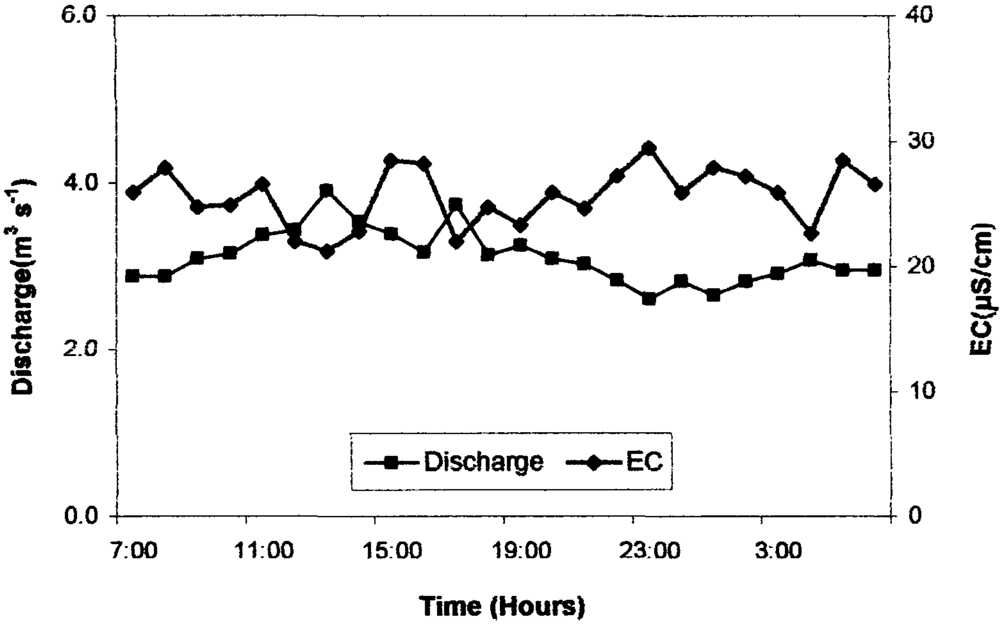


Fig. 5.20: Relationship between EC and dishcarge for hourly sampling conducted on August 15-16, 2001

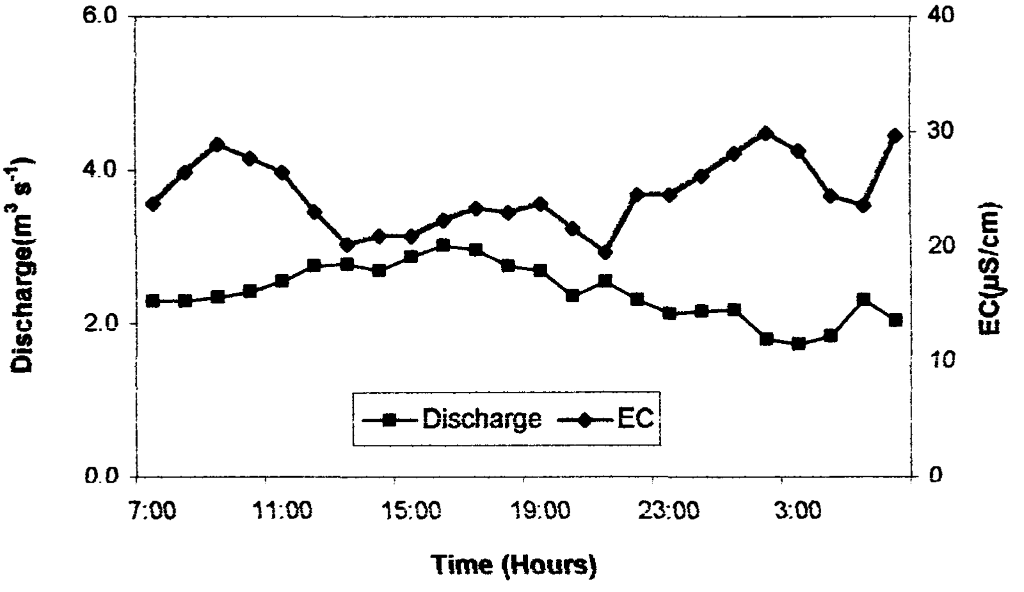


Fig. 5.21: Relationship between EC and discharge for hourly sampling conducted on August 30-31, 2001

Fig. 5.22: Percentage change in solute flux and discharge on July 13-14, 1999

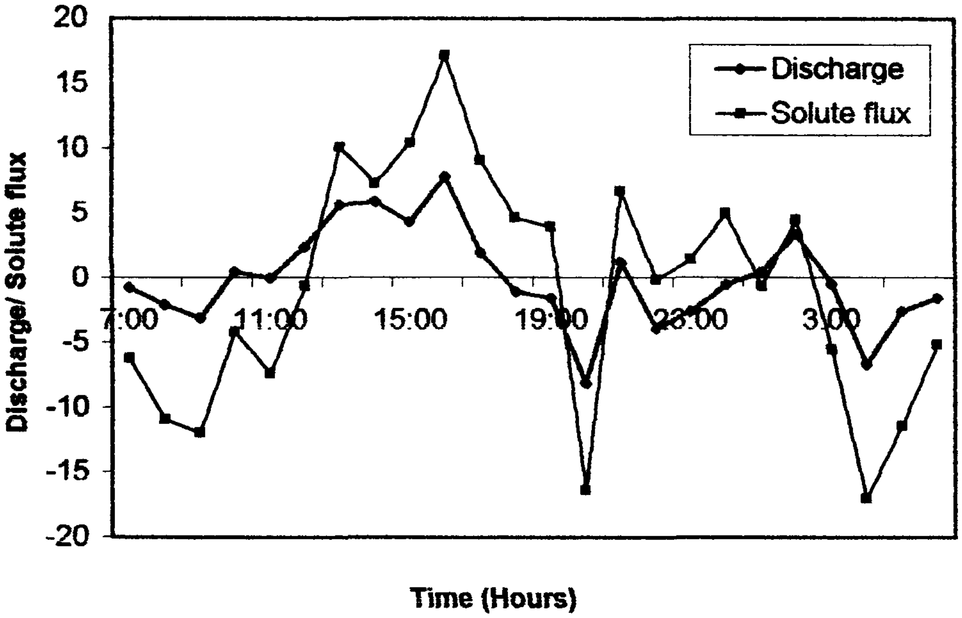


Fig. 5.23: Percentage change in solute flux and discharge on July 30-31, 1999

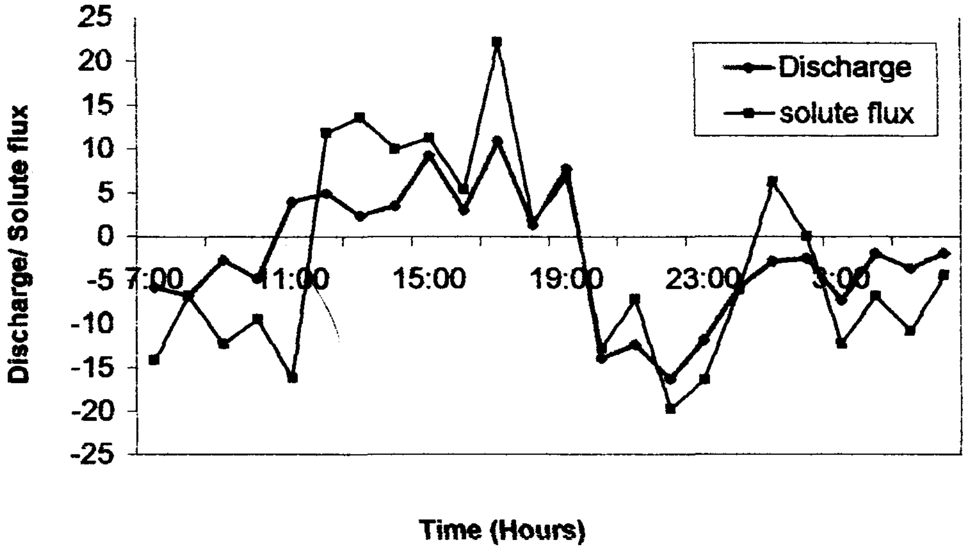


Fig. 5.24: Percentage change in solute flux and discharge on August 14-15, 1999

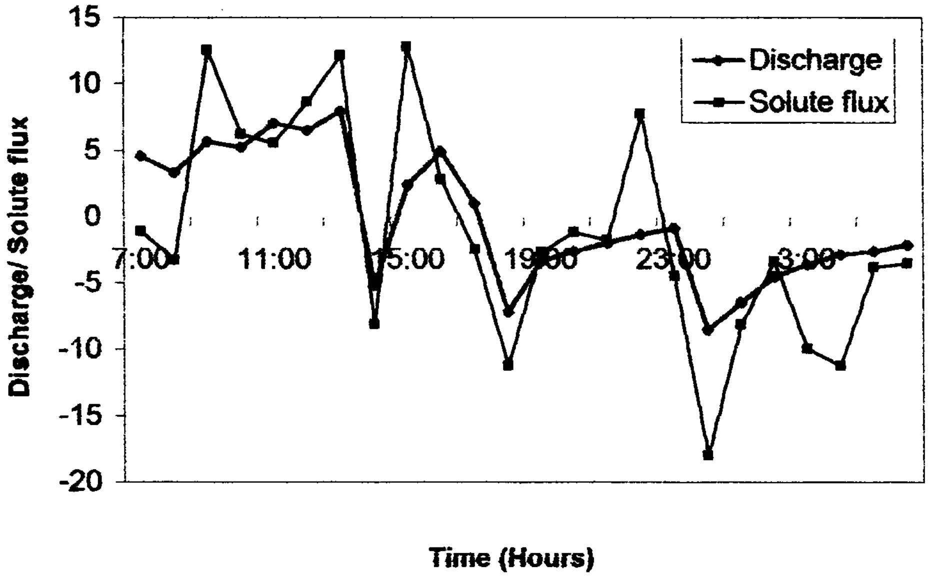


Fig. 5.25: Percentage change in solute flux and discharge on August 30-31, 1999

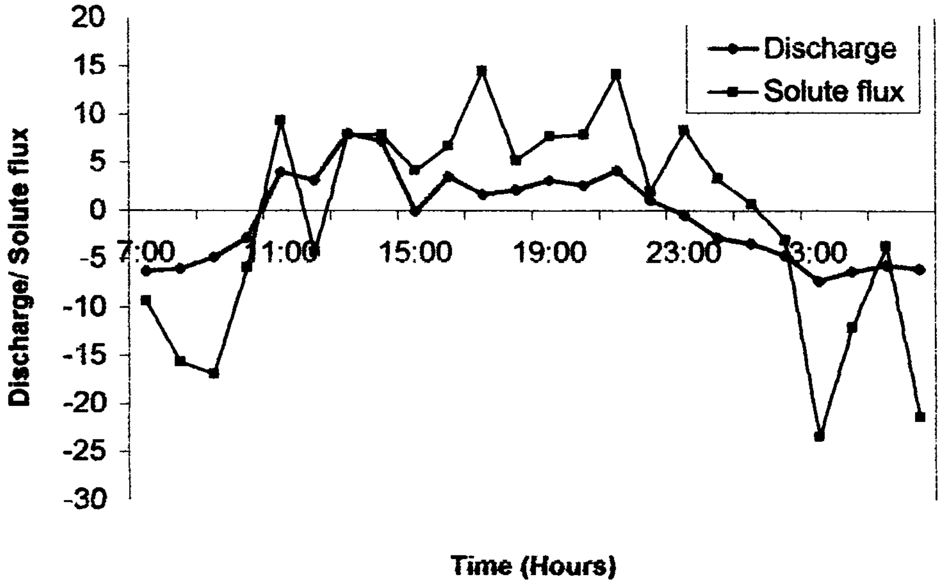


Fig.5.26: Seasonal variation of EC and discharge,1999

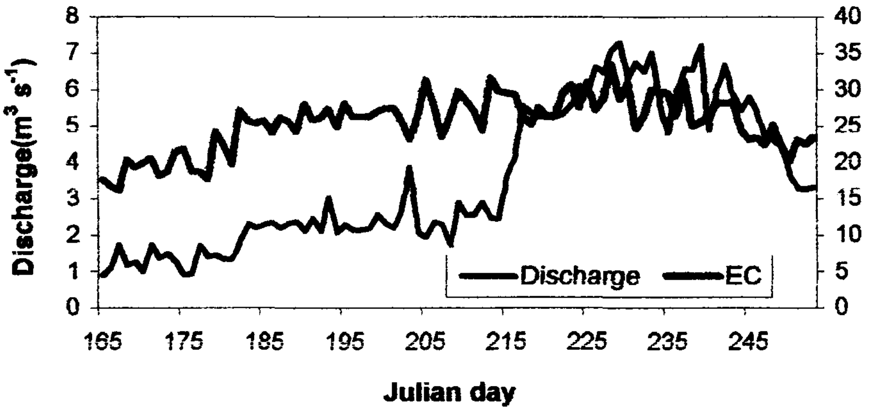


Fig. 5.27: Seasonal variation of EC and discharge for 2000

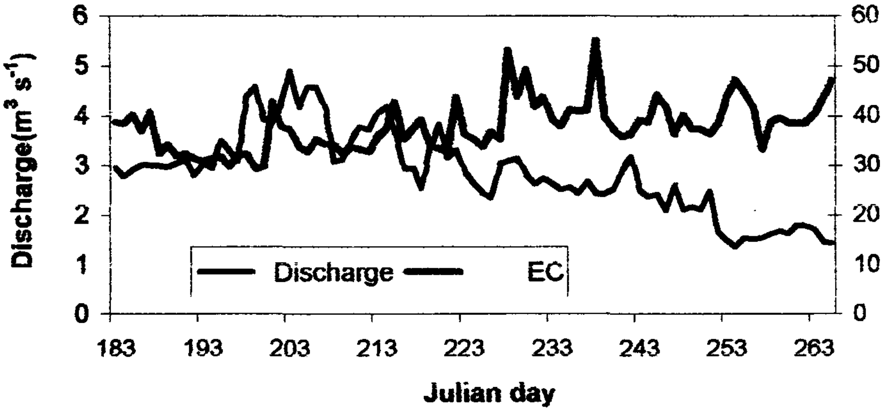
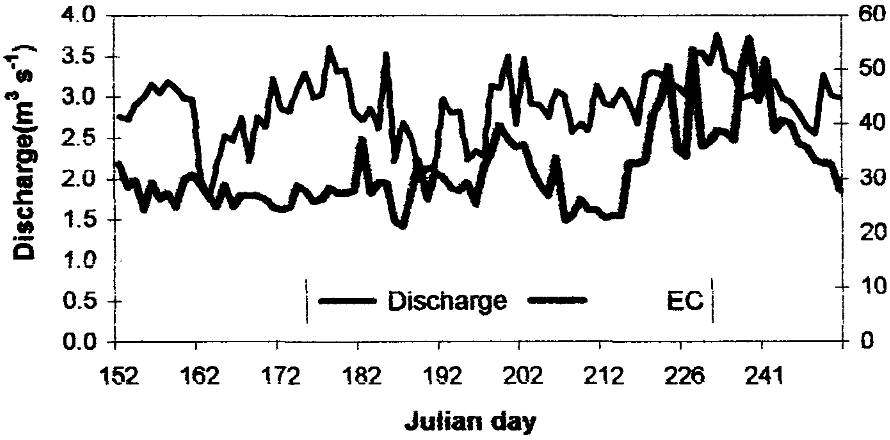


Fig. 5.28: Seasonal variation of EC and discharge for 2001



(1994) examined differences between proglacial suspended sediment transport from an Arctic and Alpine glacier. For the Himalayan region, runoff and sediment transportation studies for some glaciers (Singh et al., 1995, Hasnain and Thayyen, 1999) have shown that the concentration of suspended sediment in meltwater is highly variable. It has been suggested that this variability results due to changes in sediment supply from the subglacial channel system (Ostrem, 1975), which may reflect the seasonal development of the subglacial drainage system (Collins, 1989). In this study, seasonal pattern of suspended sediment transport in the Proglacial stream draining from Dokriani glacier is examined with a view to identify relationship between hydrological characteristic and sediment delivery.

Suspended sediment concentration (SSC) and discharge measurements were carried out on Dokriani glacier meltwater stream known as Din Gad between June and September 1999, between July and October 2000 and between June and September 2001.

Seasonal variations in suspended sediment and its relationships with discharge for the ablation seasons 1999 and 2000 have been shown in Fig 5.29 and 5.30. In the ablation season 1999 discharge increased slowly from June to July, thereafter a rapid increase was obtained with a peak at the end of August. In the ablation season 2000, the discharge pattern gained its peak in July and declined by mid August. This is probably due to complex impact of high intensity monsoonal rainfall periods (Collins, 1996; Collins and Hasnain, 1994) of August in 1999 and July in 2000. Increase in discharge is associated with increase in suspended sediment. It has been observed that high flow in July and August transport the highest monthly sediment loads. Mean monthly suspended sediment load for the ablation season 1999 and 2000 has been shown in Table.5.9 and 5.10. From the beginning of September there is recession of both discharge and sediment load.

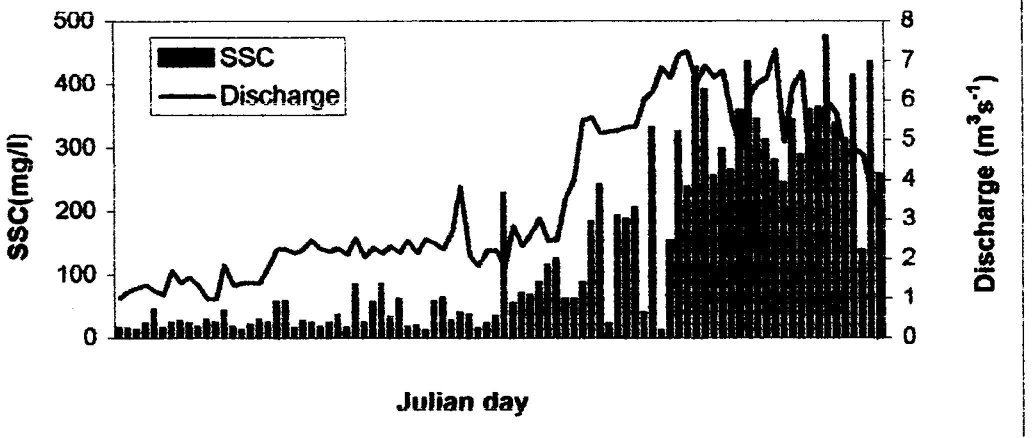


Fig. 5.29:Relationship between SSC and Discharge for ablation season 1999

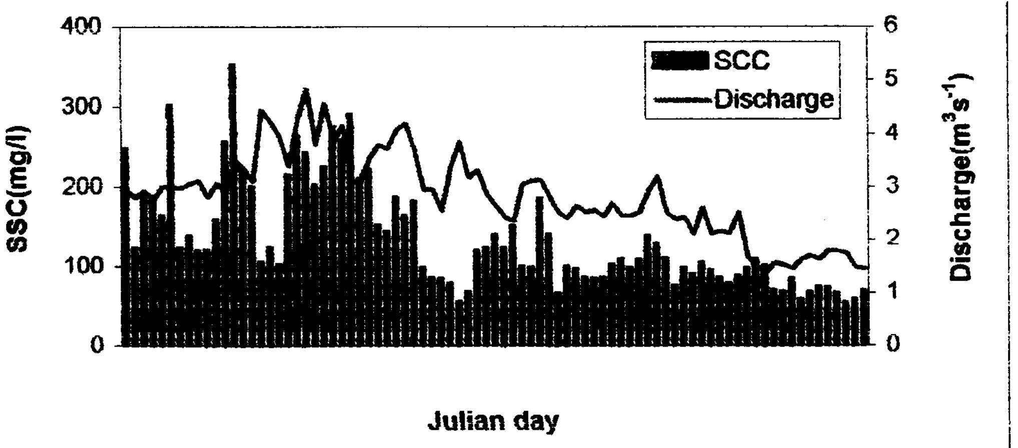


Fig. 5.30:Relationship between SSC and Discharge for ablation season 2000

Table 5.9: Monthly suspended sediment transport of Dokriani glacier in the ablation season, 1999

Month	Suspended sediment flux (tons/km^2/month)	Suspended sediment flux (In percentage)
June	393	3.0
July	3658	26.0
August	6086	43.0
September	3875	28.0

Diurnal variations in discharge (Q) and suspended sediment concentration (SSC) are characteristic of glacier fed rivers, reflecting diurnal variations in radiative energy input. The relationship between suspended sediment concentration (SSC) and discharge (Q) for the Dokriani glacier varies through different stages of the ablation season. In 1999 there is a weak association between suspended sediment concentration and discharge for the month of July in comparison with other months. In other months, association is high, particularly in the month of September, when intensity of monsoonal rain is declining and sediment availability in high. For ablation season 2000 suspended sediment concentration (SSC) and discharge has good bearing in July and September. Weak association has been found for the month of August, again indicating the complex impact of high intensity monsoonal rainfall.

A total of 14012.0 tons/km^2/yr. and 18710.0 tons/km^2/yr of suspended sediment are transported from the Dokriani glacier basin in the ablation seasons of 1999 and 2000 respectively. About 43% of sediment transport in 1999 occurred in August along with the highest volume of discharge. The sediment transport and discharge in the month of July and August 1999 combined was 69% and 61% respectively of the total seasonal sediments transport and discharge. In the year 2000, highest sediment is transported in the month of July (Table 5.10) with the value of 8240 tons/km^2/yr i.e. 44% of the total sediment transported in the year.

Table 5.10: Monthly suspended sediment transport of Dokriani glacier in the ablation season, 2000

Month	Suspended sediment flux (tons/km^2/month)	Suspended sediment flux (In percentage)
July	8240	44.0
August	6490	35.0
September	3980	21.0

The ablation zone of the Dokriani glacier is characterised by continuous surfacial cover of morainic debris as well as the dissection of ice masses (crevasses). During heavy monsoon rains (July to September) most of the debris is sluiced down through extensive longitudinal and transverse crevasses into englacial and subglacial tunnels. The supraglacial debris carried by rainwater is stored in the subglacial channels in addition to basal sediment produced by process of glacial erosion. The drainage network in early summer will supply large quantities of sediment stored from the previous year's ablation season. Many studies (Ostrem, 1975; Bezing et al., 1989) have shown that the bulk of sediment yield from the glaciers into meltwater occurs during extreme rainstorms. However it has been observed that in the Dokriani glacier basin, sediment yield of meltwater exhibits great variations throughout the ablation season. Sediment flux first displays the spring rise in discharge when the occurrence of monsoonal rainfall is negligible. During July and August increasing discharge with high sediment flux is due to monsoonal rainfall. After the cessation of rainfall by the middle of September, the discharge is mainly controlled by outflow from a slow- flowing subglacial network.

The monsoonal months of July, August and September 1999 contribute 94% of discharge and 97% of sediment transport and experience almost 99% of rainfall. During June about 3.0% of sediment is transported with 6% of discharge. The mean suspended sediment concentration (SSC) in the month of June, July, August and

September for the year 1999 was 393, 3658,6086 and 3875 tons/km^2/month respectively. Average total suspended sediment transported in the ablation season has been computed as 14102 tons/km^2/yr. During ablation season 2000, total suspended sediment transported has been computed as 18710 tons/km^2/yr. with average monthly suspended sediment transportation of 8240, 6490 and 3980 tons/km^2/month in the month of July, August and September respectively. Average suspended sediment concentration (SSC) for the years 1999-2000 has been computed as 16862 tons/km^2/ yr (Table 5.11).

Table 5.11: Suspended sediment transport rate from Dokriani glacier basin in ablation seasons 1999-2000 and comparison with other Himalayan glacier basin

Glacier and river basin	**Average seasonal sediment transport (tons/ Km^2/ yr)**	**Source**
Himalayan glaciers		
Batura, Karakoram (Pakistan)	6086	Fukushima (1987)
Langtang (Nepal)	2453	Lanzhhou Institute (1980)
Dokriani, Garhwal Himalaya (India, 1994)	15751	Hasnain (1999)
Dokriani,Garhwal Himalaya (India 1999-2000)	16862	**Present study**
Alpine- sub-alpine stream		
(Tel gad) Garhwal Himalaya (India)	620	Sarfaraz Ahmad (1999)
Proglacial Stream		
Alaknanda	356.3	Singh and Hasnain (1998)
Bhagirathi	316	Pandey and Singh (1999)
Main River (Ganga)	591	Subramaniun (1993)

5.8 EFFECTS OF CLIMATE VARIABILITY ON RUNOFF CHARACTERISTICS

In high altitude, monsoonal precipitation is in the form of snow and constitutes a major input to glacier mass balance (Ageta and Kadota, 1992). Amount of precipitation brought from monsoonal trajectories on the surface of Himalayan glacier is sensitive to ambient air temperature (Ageta, 1983). As global warming continues, the increased air temperature in high mountain areas may lead to fast retreating of glaciers fed by monsoonal precipitation (Fujita et al., 1997; Hasnain, 1999; Naito et al., 2000). Hydrology of the meltwater stream draining from Indian Himalayan glaciers is sensitive to climate variability and any slight change may affect the ecohydrology of the region. Hence it is important to understand the effect of climate variability on runoff in the meltwater stream.

For the purpose of evaluating effect of climate variability on runoff characteristic, discharge measurements were carried out about 600m downstream from the glacier snout, which has a 10m straight reach. Frequent cross-section measurement was carried out during ablation period using a dipstick. Flow velocity was measured with a standardised wooden float and water level monitored after establishing a wooden staff gauge. Discharge was calculated from the rating curve. Self-recording rain gauge was installed for continuous recording of precipitation at 3900m elevation. Daily maximum and minimum air temperature was recorded in the years 1999, 2000 and 2001 at an elevation of 3900m near the base camp during the ablation season. Daily average temperatures were computed by taking average of daily maximum and minimum temperatures.

Meltwater discharges observed from hourly sampling conducted at an interval of 15 days for the entire ablation season from June to September 1999, shows peaks between 1600 and 1800 hours in July, 1300 and 1500 hours in August and at1300 hours in September (Fig. 5.31). In comparison to early ablation season the early peak in later ablation season is perhaps related to change in the sub-glacial hydrological system owing to a change in climatic conditions. The highest discharge peak among these selected dates were noticed on 15 August and 30 August. Therefore it is assumed that the period between 15 August and 30 August 1999 coincides with widespread changes in subglacial drainage network as reported elsewhere (Rothlisberg, 1972; Rothlisberg and Lang 1987). Similar trend has been observed for the year 2000 (Fig. 5.32). High intensity monsoonal rain of July and August had probably opened up the internal drainage system to the efficient channelised system. However, in the ablation season 2001 the highest peak (Fig. 5.33) in all the selected dates have been found to be between 1600 and 1900 hours. Few multiple peaks have been obtained on diurnal hydrographs. The multiple peaks result from the variation in radiative energy inputs through monsoonal cloud cover (Hasnain, 1999). It has been found that in late September 1999 and 2001 hydrograph has a short rising limb and an extended recession limb suggesting reduced meltwater contribution, especially from upper ablation region and contraction of the glacial drainage system, while in the year 2000 discharge started rising again from 1.00 hrs. as contribution from higher elevation reached the glacier portal. Therefore it is inferred that the shape of hydrograph is influenced by various parameters, notably by the intensity and amount of precipitation at different elevation levels.

The monsoonal rainfall has impact on both temporal pattern and quantity of runoff derived from glacier. It has been observed by Ageta (1983) that under warm temperature conditions, high intensity monsoon rain occurs over the entire elevation range of glacier because snowfall changes to rain under warm temperature conditions, resulting in increased melting of snow cover. The winter snow cover, summer cloud cover, and summer snowfall reduces energy inputs for the melting. However, the effect on runoff may to an extent, be offset by rain during the summer monsoon period. In all the cases discharge peak has been obtained in the month of July/August, due to high intensity monsooanl rainfall. However, from mid July to early September thick monsoonal cloud cover in the entire Garhwal Himalaya reduces the insolation, hence resulting into substantial reduction in meltwater contribution and the discharge

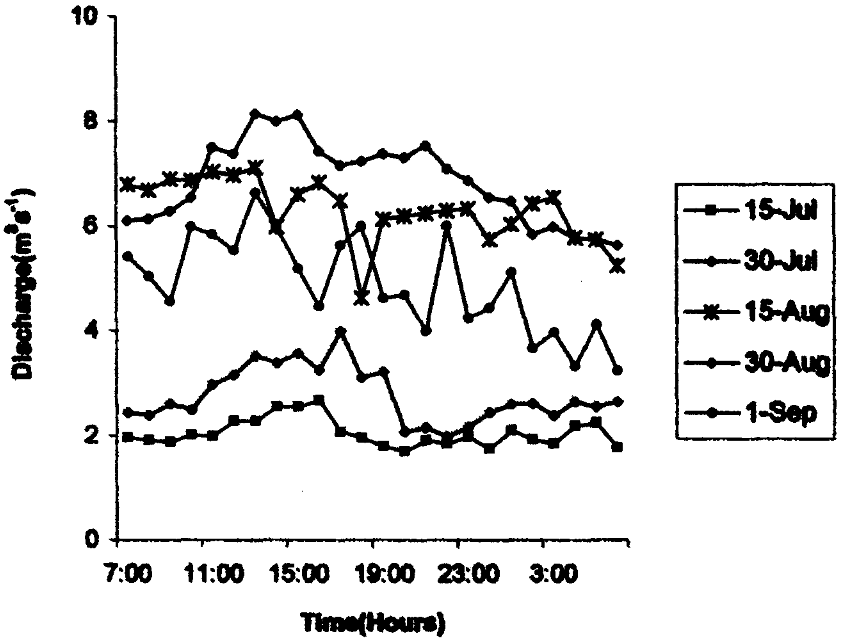


Fig. 5.31: Diurnal Variations of discharge for hourly sampling conducted between June and September,1999

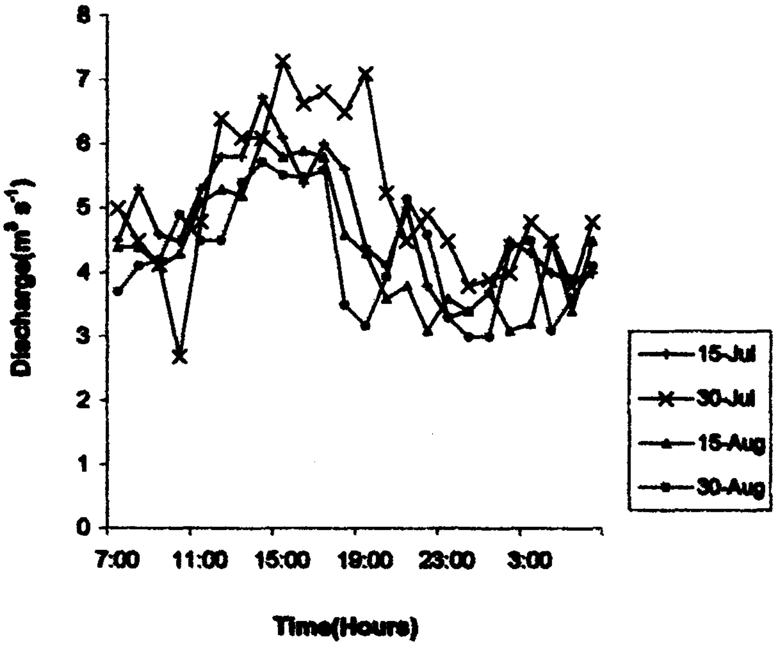


Fig.5.32: Diurnal variation of discharge for hourly sampling conducted between July and September, 2000

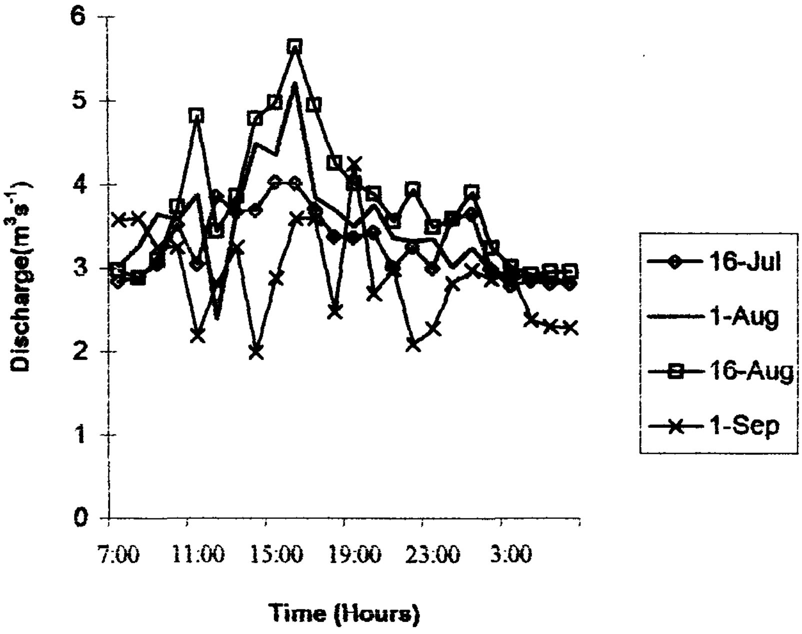


Fig.5.33: Diurnal variation of discharge on specific dates between June and September 2001

is sustained by runoff, generated by monsoonal rain. As a result of radiation interception by cloud cover the resulting hydrograph shows very distinct bite during the monsoonal period between July and September (Collins and Hasnain, 1994; Hasnain et al., 2001). From mid September the discharge gradually reduces as the atmospheric temperature steadily falls. Analysis of data shows that diurnal variability in suspended sediment is much higher than the discharge and largest variations in suspended sediment concentrations were associated with runoff of peak melt season.

For analysing the effects of climate, hydrological data collected for four consecutive ablation seasons between 1994-1997 by (Hasnain, 1995, 2001) have been taken into account. These four years data along with data collected in the ablation seasons 1999, 2000 and 2001 have been subjected to the verification of effects of climate change on the glacier basin. The average temperature between 1994 and 1998 was recorded to be about 10°C for the months of July and August taken together when rainfall as well as discharge was highest. As per IPCC, the decade of 1990s had been the warmest in last century. This is showing effect on Dokriani glacier also, resulting into increased liquid precipitation and corresponding increased discharge. The anomalous high rates of glacier shrinkage by climate warming have resulted in high runoff. Fig 5.34 shows temperature, precipitation and discharge trends likely to continue between years 1994-2010. The trend establishes the fact that as the temperature goes on increasing it will have effect on monsoonal rain that will result in increase in glacial runoff particularly in the monsoonal months of July, August and September.

5.9 CONTRIBUTION OF MONSOONAL RAIN TO TOTAL GLACIER RUNOFF

Runoff derived from the glaciated catchments induced by rainfall can be divided into two components; one is the direct contribution of liquid water from atmosphere to the system, and the second is ice and snowmelt due to the monsoonal precipitation. The icemelt induced by the rainfall events is considered to the minimal but accountable with total icemelt component. There is extreme variability in precipitation over the

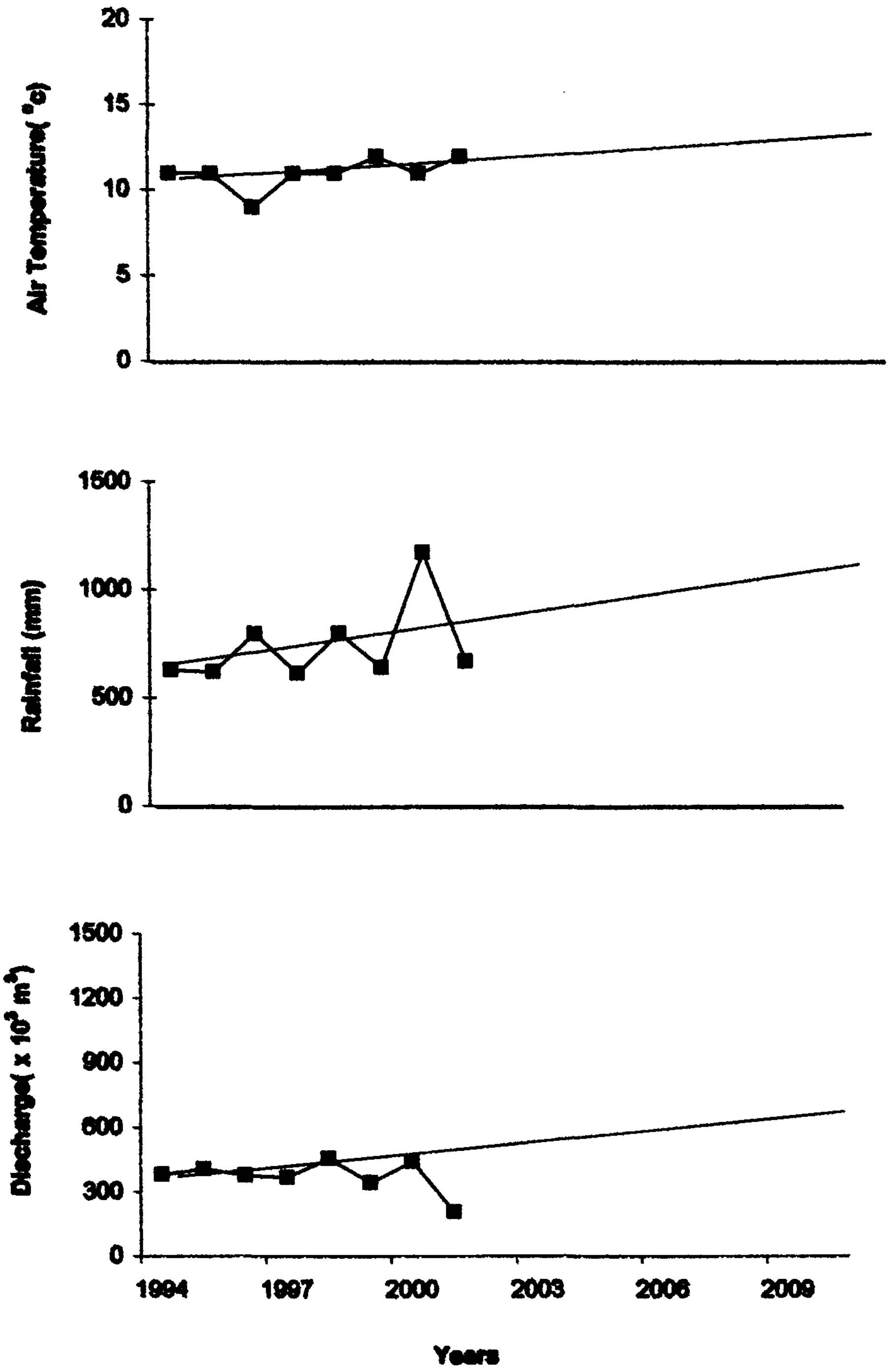


Fig. 5.34: Projected trends in precipitation, air temperature and runoff between 1994 and 2010 in Bhagirathi- Ganga basin

Dokriani glacierised basin, which is evident from the rainfall (as well as temperature) recorded during the ablation seasons 1999, 2000 and 2001 (Fig. 5.35)

To separate the daily rainfall component from the discharge at gauging station mass balance relationship can be used. The runoff characteristics of glacierised and non-glacierised regions are different; therefore it is customary to divide the whole basins into two parts. The total area of Dokriani basin is 10 km^2, out of which glacierised area is 6 km^2 and non-glacierised area is 4 km^2. The liquid precipitation falling over glacierised area is analogous to the channel precipitation, it joins the supraglacial meltwater channel and routed to the glacier portal through the glacial drainage system without major losses. But the rainfall over the non-glacierised area of the basin accounts for the major losses mainly due to infiltration. Considering steep bare slope of non-glacierised part of the basin, a runoff coefficient of 0.7 (Mutreja, 1986) is considered to be good for the calculation. Due to very low temperature, evaporation factor is negligible and the area of higher altitude experiences solid precipitation during the monsoonal months. It has been observed by Hasnain and Thayyen (1994) that area above 5400-5500m experiences temperature < 2°C for most of the days and hence is considered to be experiencing solid precipitation. The following relationship can be used to separate the rainfall component from the daily glacial discharge.

For glacierised region $Rpg = P \times Ag$

For non- glacierised region $Rpn = P \times An \times 0.7$

$RpT = Rpg + Rpn$

Where Rpg is the rainfall contribution from glacierised zone, Rpn, is the rainfall contribution from non- glacierised zone, RpT, the total daily rainfall contribution (m^3), P is the precipitation in mm, Ag is the area of glacierised zone of catchment where temperature > 2°C, An is the non- glacierised zone of the catchment where temperature > 2°C. But due to logistic reasons separate data from glacierised and non- glacierised area of the basin could not be collected. The meteorological parameters like temperature and rainfall were collected near the base comp, which is near the glacier snout. These data gave an idea of the monsoonal rain contribution to

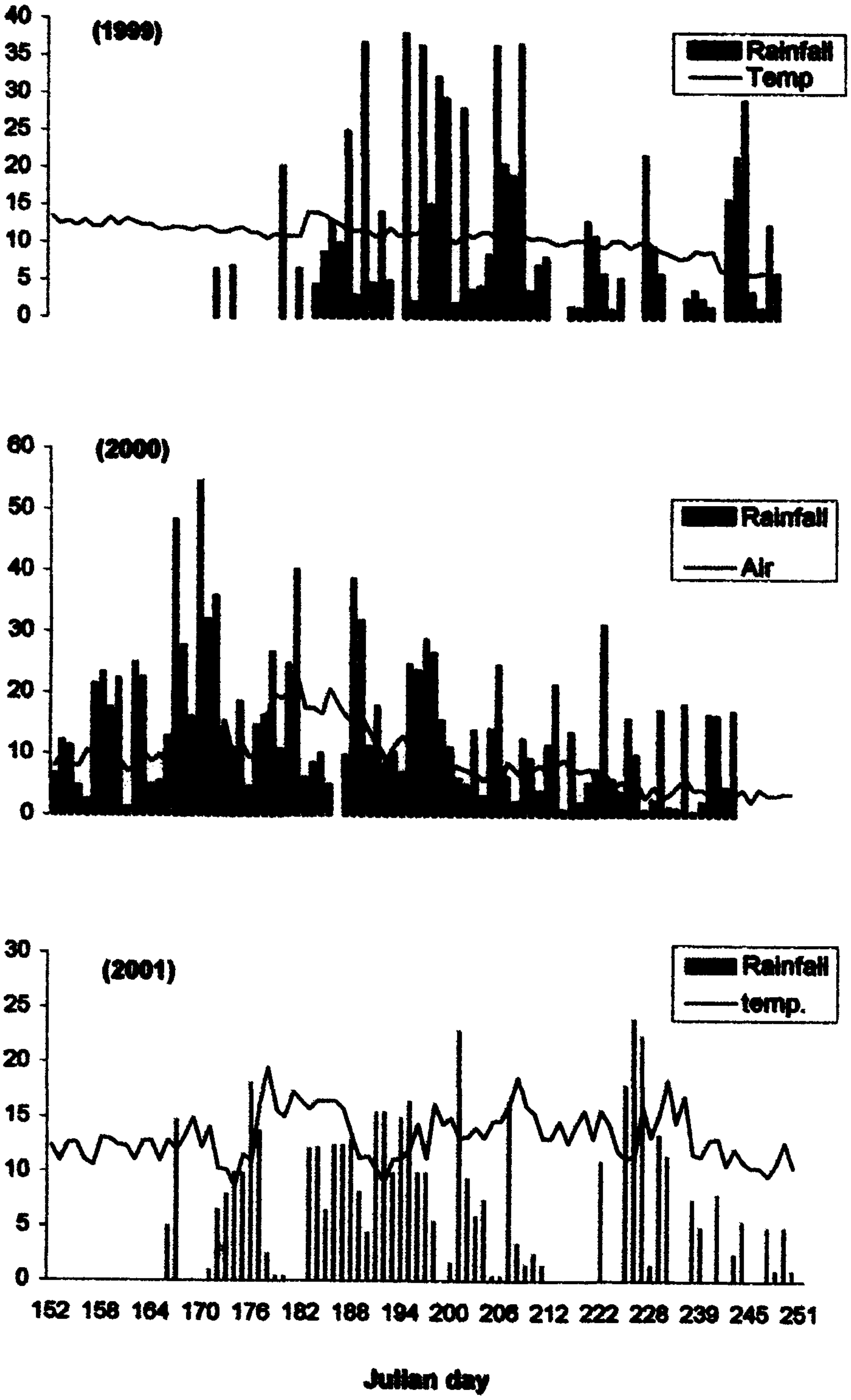


Fig. 5.35: Rainfall and Temperature record for ablation seasons (1999- 2001)

the total discharge of the stream emerging from the Dokriani glacier. Total catchment area of Dokriani glacier is 10 km^2, out of which 6 km^2 is glaciated, and 4km^2 is non-glaciated. 4.2 km^2 out of 6 km^2 glaciated area experiences liquid precipitation, while 2.1 km^2 out of non-glacierised area of 4 km^2 area experiences liquid precipitation during the monsoonal months (Hasnain and Thayyen, 1994). The separated rainfall component of the total runoff has been shown in (Fig 5.36 to 5.38). The total rainfall experienced by Dokriani glacierised basin during the ablation seasons of 1999, 2000 and 2001 was 630mm, 1279mm, and 542mm respectively. With the advance of monsoonal period, the cloud cover effectively reduces the solar energy reaching the ground and hence reduces the melt rate. Recessional trends shown by both total hydrograph and corrected hydrograph for rainfall component for the monsoonal months proves that the reduction in melt rate due to the reduced energy input is not compensated by the rainfall.

The average discharge for Dokriani glacier basin during ablation seasons of 1999, 2000 and 2001was estimated to be 3.41 m^{3}s^{-1}, 5.40 m^{3}s^{-1}, and 2.90 m^{3}s^{-1} respectively. Average discharge for the observation period (1999-2001) was 3.90 m^{3}s^{-1}. In the ablation seasons 1999, 2000 and 2001 average discharge per day was recorded as 345x10^{3}m^3, 485x10^{3}m^3 and 240x10^{3}m^3 respectively and rainfall components (components of glacier runoff) were 48x10^{3}m^3, 75x10^{3}m^3 and 35x10^{3}m^3 respectively. Average total discharge in the ablation season 1999-2001 has been computed as 310x10^{5}m^3, 436x10^{5}m^3 and 288x10^{5}m3 respectively. Rainfal component for the season 1999-2001 has been computed as 63x10^{5}m^3, 85x10^{5}m^3 and 48x10^{5}m^3 respectively. In terms of percentage the monsoonal rain contributed 11%, 15% and 14% in ablation season 1999, 2000 and 2001 respectively and snow and ice component for the ablation seasons 1999, 2000 and 2001 contributed 89%, 85% and 86% respectively. Therefore, on an average the monsoonal rainfall contributed about 13% of the total discharge in the ablation seasons 1999-2001. The results of the individual component (monsoonal rain and snow/ice) to the total glacier runoff for Dokriani glacier between 1994-2001 have been shown in Table 5.12. Mean monthly values od discharge and matereological

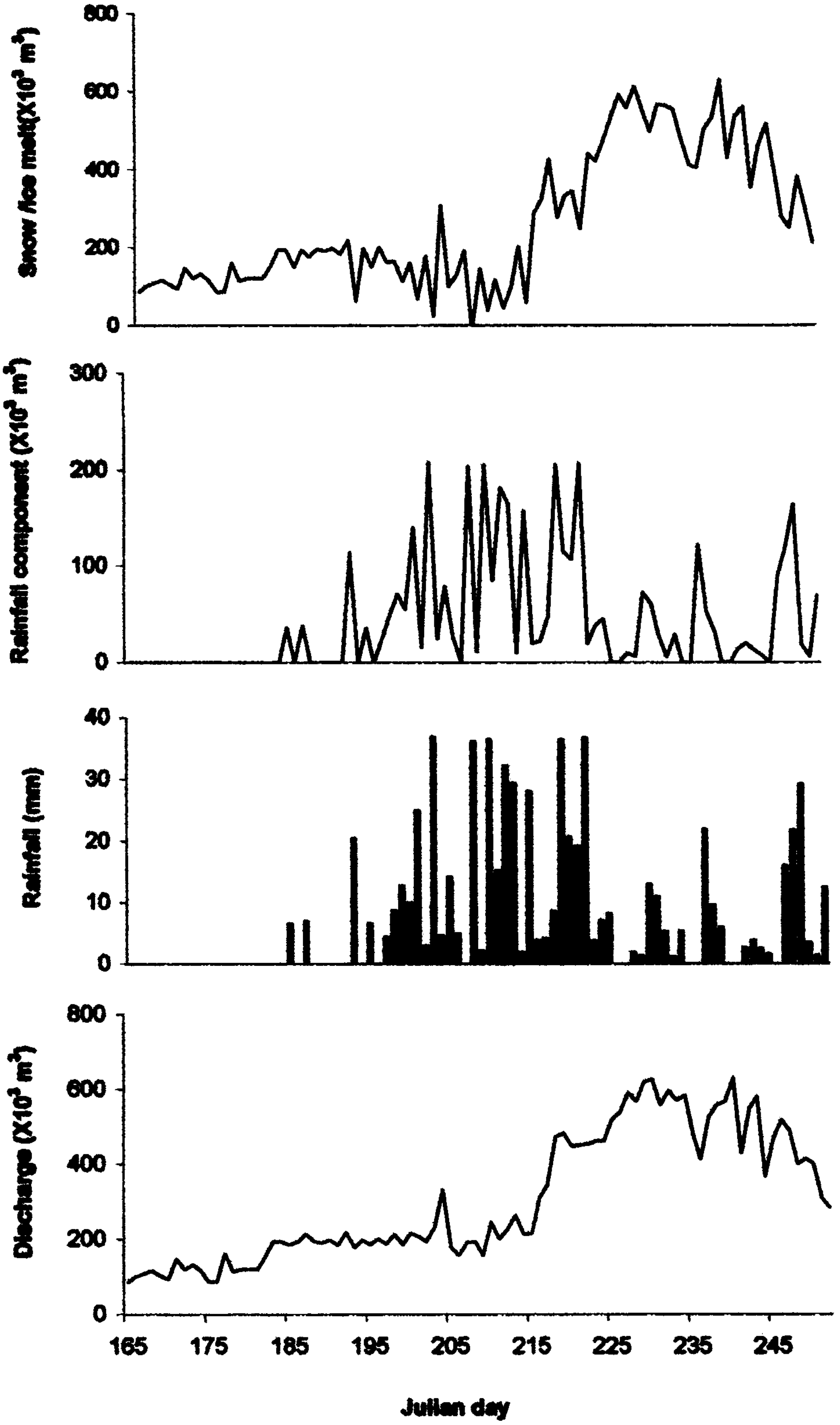


Fig. 5.36: Seperated components of total runoff for ablation season 1999

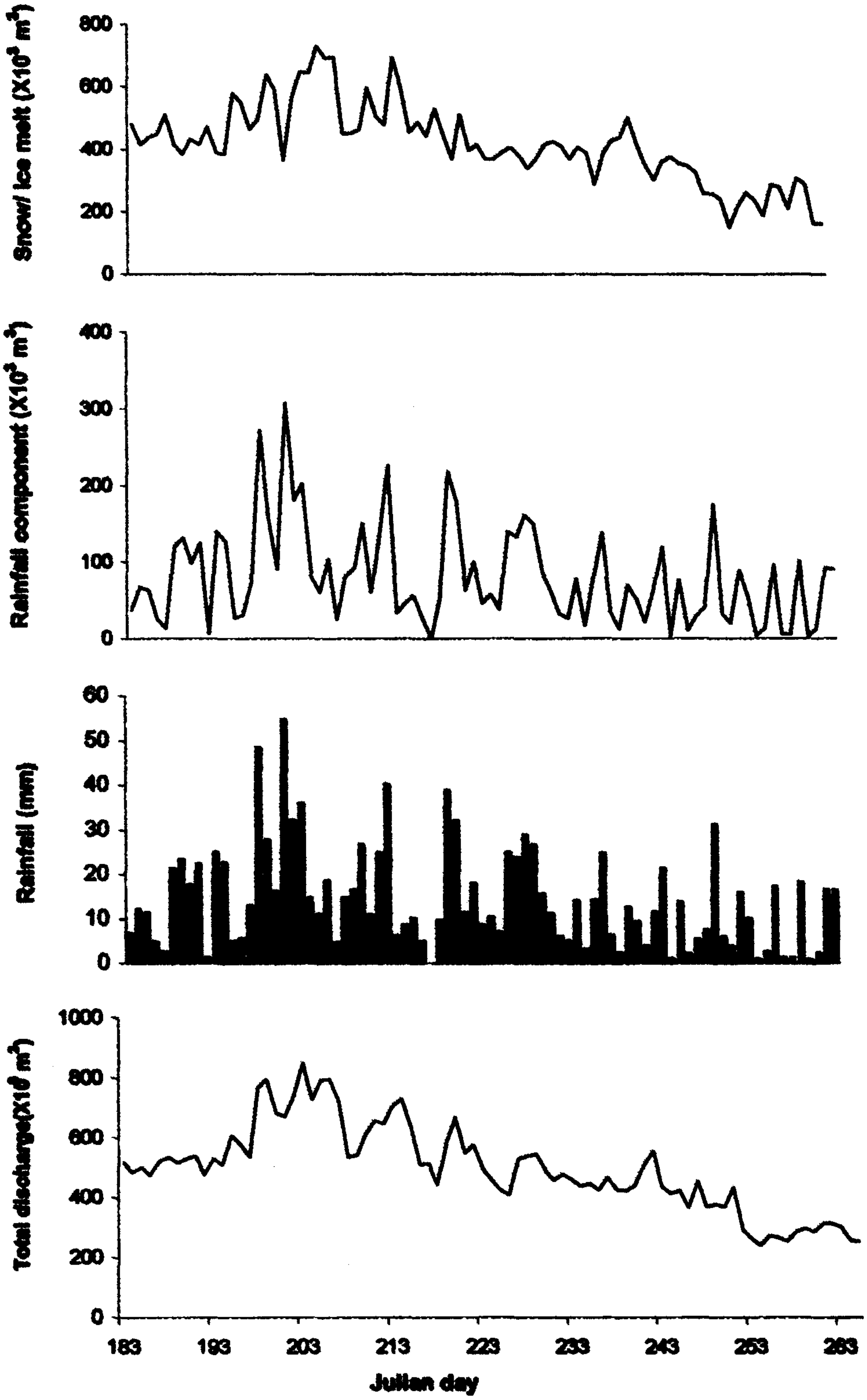


Fig. 5.37: Separated components of total runoff for ablation season 2000

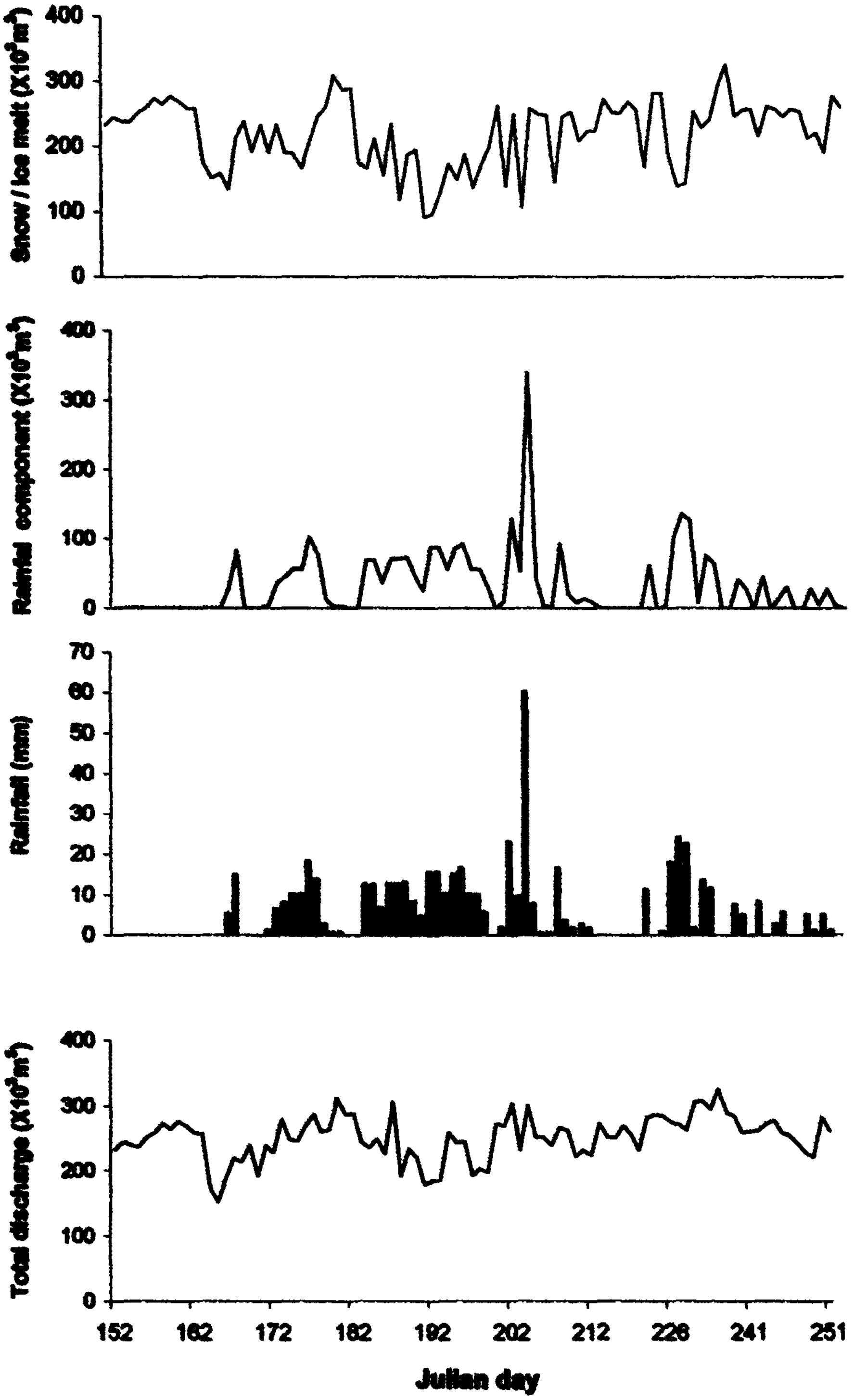


Fig.5.38: Separated components of total runoff for ablation season 2001

parameters for the months of July and August between 1994-2001 have been shown if Table 5.13 and 5.14.

Table 5.12: Separated components of bulk hydrograph from 1994 - 2001

Year	Av. Total discharge ($10^3 m^3$)	Rainfall ($10^3 m^3$)	Snow /ice ($10^3 m^3$)	Rainfall (%)	Snow/ice (%)	Source
1994	243	33	210	13	87	Hasnain (1995)
1995	266	34	232	13	87	Hasnain (2001)
1996	468	57	411	12	88	Hasnain (2001)
1997	720	63	657	9	91	Hasnain (2001)
1999	345	48	297	11	89	**Present study**
2000	485	75	410	15	85	**Present study**
2001	240	35	205	14	86	**Present study**

Table5.13: Mean monthly values of discharge and meteorological parameters for July observed during 1994-2001 for Dokriani glacier basin

Years	**Discharge** **(m^3s^{-1})**	**Temperature** **(°C)**	**Precipitation** **(mm)**	**Source**
1994	6	11	17	Hasnain (1995)
1995	5	11	10	Hasnain (2001)
1996	2	9	6	Hasnain (2001)
1997	5	11	8	Hasnain (2001)
1999	4.1	12	9	**Present study**
2000	7	11	18	**Present study**
2001	2.5	12	12	**Present study**

Table 5.14: Mean monthly values of discharge and meteorological parameters for August observed during 1994-2001 for Dokriani glacier basin

Years	**Discharge** **(m^3s^{-1})**	**Temperature** **(°C)**	**Precipitation** **(mm)**	**Source**
1994	5	8	15	Hasnain (1995)
1995	5	10	9	Hasnain (2001)
1996	2	9	6	Hasnain (2001)
1997	6	9	10	Hasnain (2001)
1999	3.6	10	7	**Present study**
2000	5.7	11	11	**Present study**
2001	3.1	11	10	**Present study**

5.10 HYDROLOGICAL SYSTEM OF THE GLACIER AND ITS RELATIONSHIP WITH DISCHARGE

To understand the hydrological system of the glacier and its relationship with discharge, dye tracer experiment was conducted in the ablation season 2000. The injection of tracers into sub-surface flow in glaciers provides information about flow paths, flow speed and passage geometry (Fountain, 1992, 1993; Hasnain et al., 2001). Rhodamine-WT of 1ppm concentration was used as a tracer. Three moulins were chosen for the experimental purposes. Moulin 1 (denoted by symbol J1) was at a distance of 900m up-glacier from the fluorometer station. Similarly moulin 2 and moulin 3 (denoted by symbols J2, J3 respectively) were at a distance of 1700m and 2300m up-glacier respectively from the fluorometer station. First experiment on moulin 1 (J1) was conducted on 8 July. 40ml of Rhodamine dye was injected at 11:32 hrs. The travel time of dye peak concentration recorded was 32.8 minutes with a straight-line transit velocity of 0.47 ms^{-1}. Similarly stream discharge at the time of dye injection and at the time of dye peak were also calculated which were of the values of 4.6 m^3s^{-1} and 6.0 m^3s^{-1} respectively. The average discharge during the test period was found to be 5.2 ms^{-1}. The second experiment on the moulin 1 (J1) was conducted on 20th August. The dye of 40ml. was injected at 10. 35 hrs. Result showed the straight–line transit time of 144 minutes with a transit velocity of 0.11ms^{-1}. The stream discharges at the time of injection and at the time of dye peak were 3.4 m^3s^{-1} and 5.8 m^3s^{-1} respectively with the average discharge of 4.6 m^3s^{-1}. Dye concentration curve resulting from injection at moulin 1(J1) on July 8 and August 20 is shown in (Fig 5.39 and 5.40). On 9 and 21 August experiments were conducted on moulin 2 (J2), at a distance of 1700m up-glacier from the measurement site. Keeping the dye concentration constant the travel time was recorded 76.4 minutes and 219.2 minutes for the experiment conducted on 9 and 21 August respectively. The average discharges observed were 6.4 m^3s^{-1} and 5.4 m^3s^{-1} respectively. The injection on 21 August, yields a curve characterised by a delayed and dispersed concentration with a travel time of 219.2 minutes and straight-line transit velocity of 0.13 ms^{-1} The dye concentration curve for J2 is given in Fig 5.41 and 5.42. Six-tracer experiments were conducted on

Fig. 5.39: Dye Concentration curve for J1 on 8 July 2000 at Dokriani Glacier

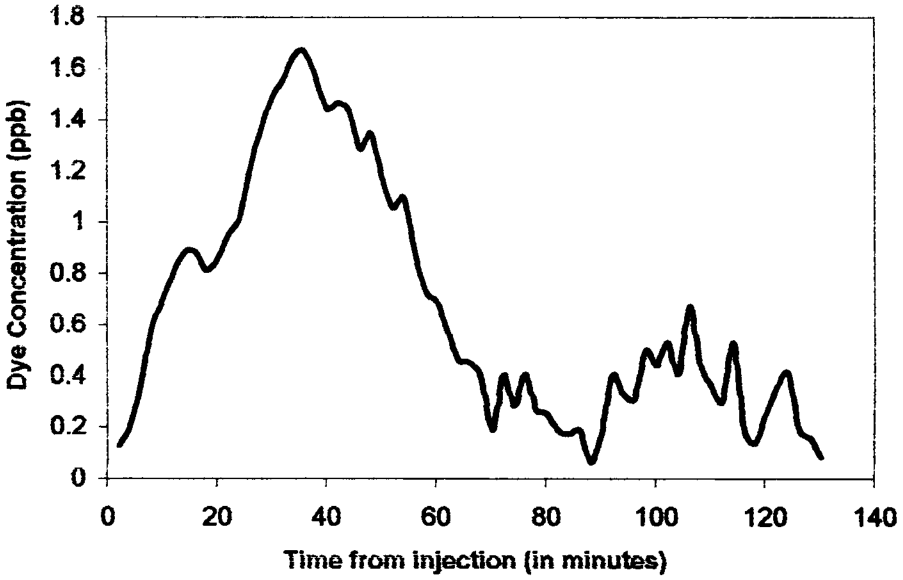


Fig. 5.40: Dye Concentration curve for J1 on 20 Aug 2000 at Dokriani glacier

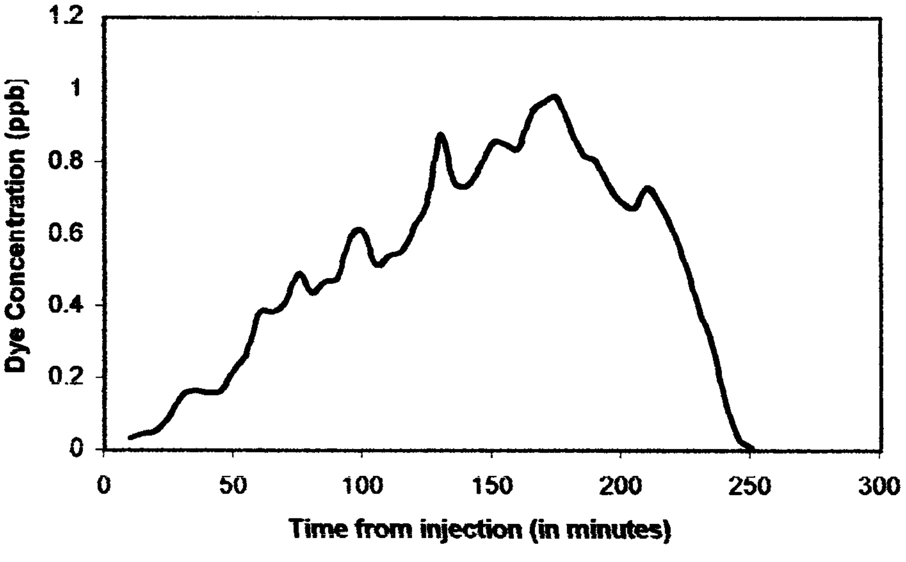


Fig. 5.41: Dye Concentration curve for J2 on 9 July 2000 at Dokriani glacier

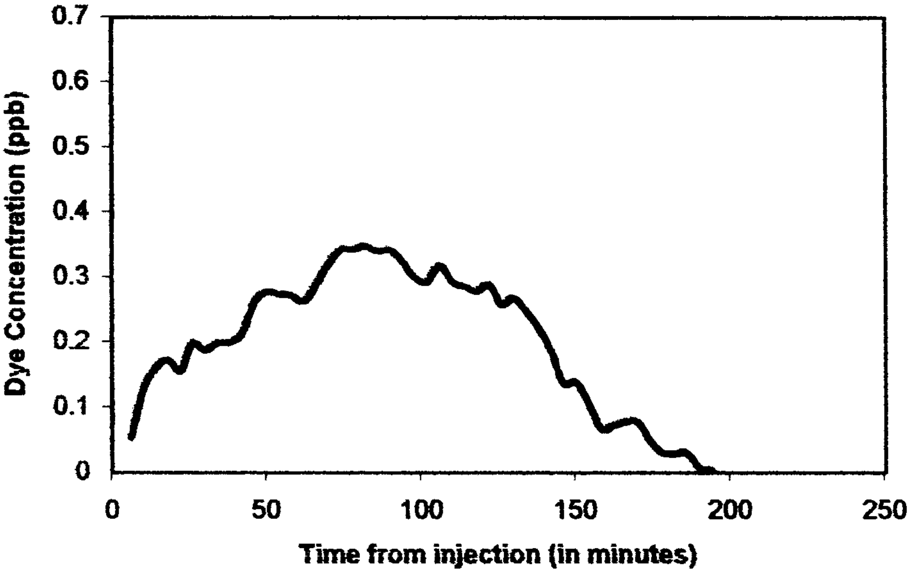
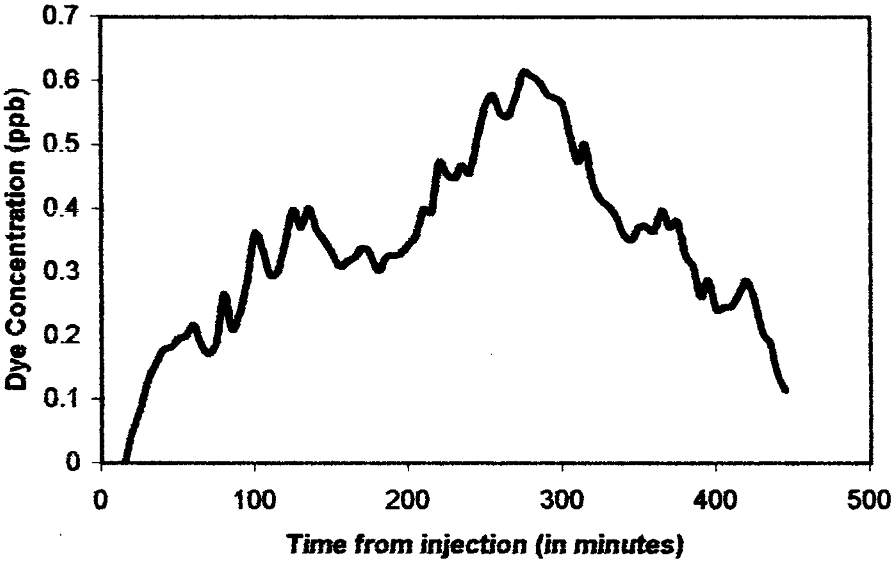


Fig. 5.42: Dye Concentration curve for J2 on 21 Aug 2000 at Dokriani glacier



moulin 3 (J3), about 2300m up-glacier from the fluorometer station. Experiments were conducted on 13 July, 23 August, 14 September, 18 September, 24 September and 28 September. This moulin is the major sink for supraglacial meltwater into the glacier. The volume of dye used (except July 13 and August 23) was 50ml. July 13 experiment is characterised by a rapid peak curve with a travel time of 90.2 minutes and yields a straight – line transit velocity of 0.43 ms^{-1}. The travel time of 348.5 minutes and 387.5 minutes were observed for the experiments conducted on August 23 and September 14 respectively, with average discharges of 4.2 m^3s^{-1} and 2.8 m^3s^{-1}. Dye concentration curves resulting from injection at JI, J2, and J3 on 8 July, 9 July and 13 July have been shown in (Fig 5.43). The 23 August injection is characterised by a delayed two-peaked curve. The time concentration curves obtained from injections conducted on 13 July, 23 August and 14 September has been shown in Fig. 5.44. Results obtained from the tracer experiment conducted on J3 in late monsoon period of 18, 24 and 28 September have been shown in Fig 5.45. During the month of September the discharge decreases considerably. Highest dispersion coefficient of 174 m^2s^{-1} was found on 9 July during the experiment on J2 with high dispersivity of 470m and it coincides with high rainfall of 22.2mm in average.

Fig 5.46 has been plotted between daily average snout discharge, air temperature and monsoonal rainfall from July to September with injection dates. It is evident from the plot that the first set of injections in July and second set of injection in August were made on very similar discharges. But the July injection were associated with velocity ranges 0.37-0.47 ms^{-1} and the August injections were associated with velocity ranges 0.11-0.13 ms^{-1}. It is therefore concluded that for such different flow velocities to result from similar discharge conditions, two different flow systems should have existed within the glacier (Nienow et al., 1996 b; Hasnain et al., 2001). The third set of experiment was conducted in September when seasonal discharges were reduced to half as compared to July and August. But the velocities show an increasing trend. During this period, water drains into moulin J3 perhaps is routed to the glacier snout via a hydrologically efficient channelised drainage system (Stenborg, 1969; Krimmel et al., 1973; Behrens et al., 1975).

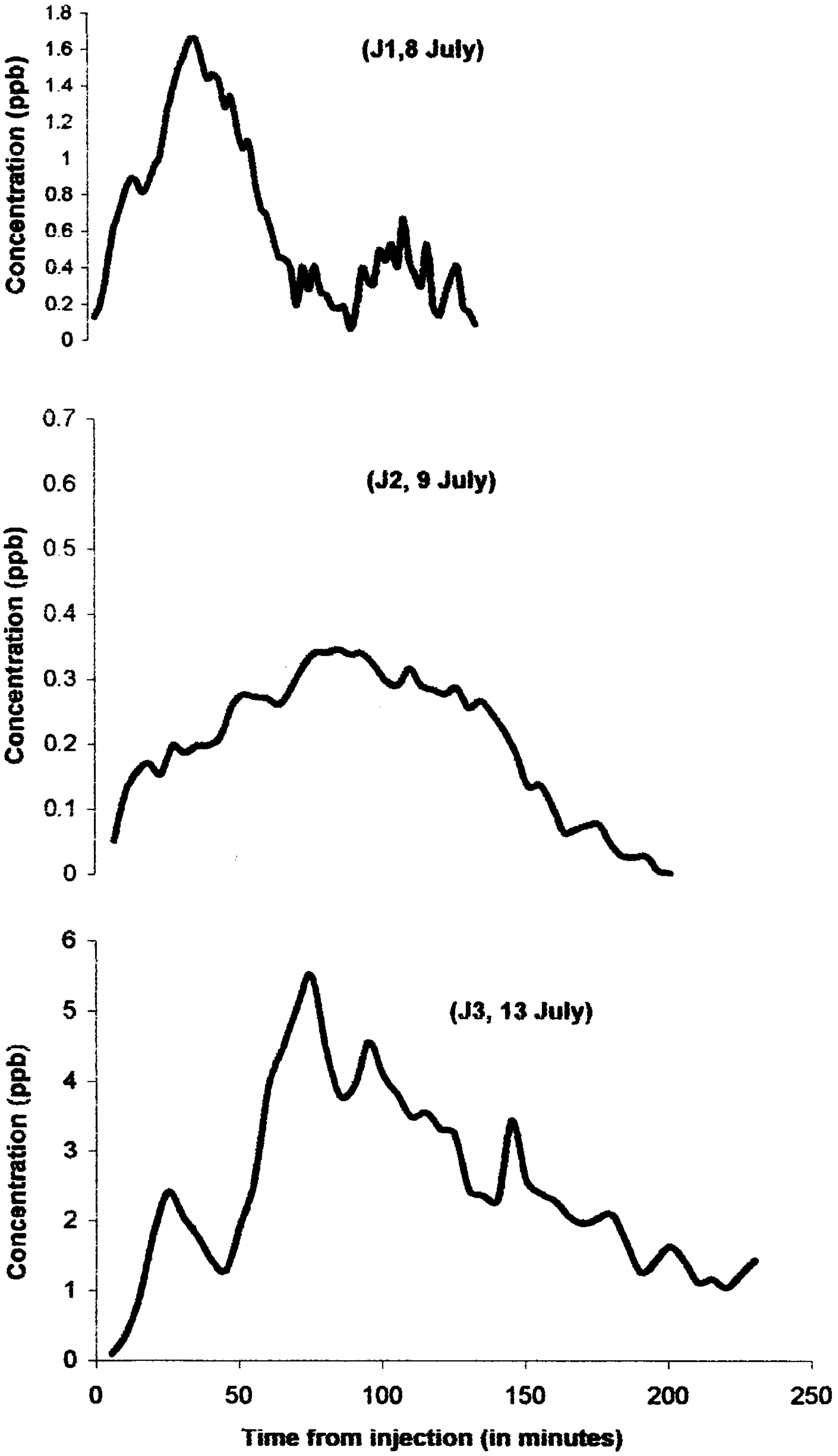


Fig. 5.43: Dye Concentration curves for J1, J2 and J3 on 8, 9 and 13 July, 2000

Fig. 5.44: Dye Concentration curves for J3 on 13 July, 23 August and 14 September, 2000 at Dokriani glacier

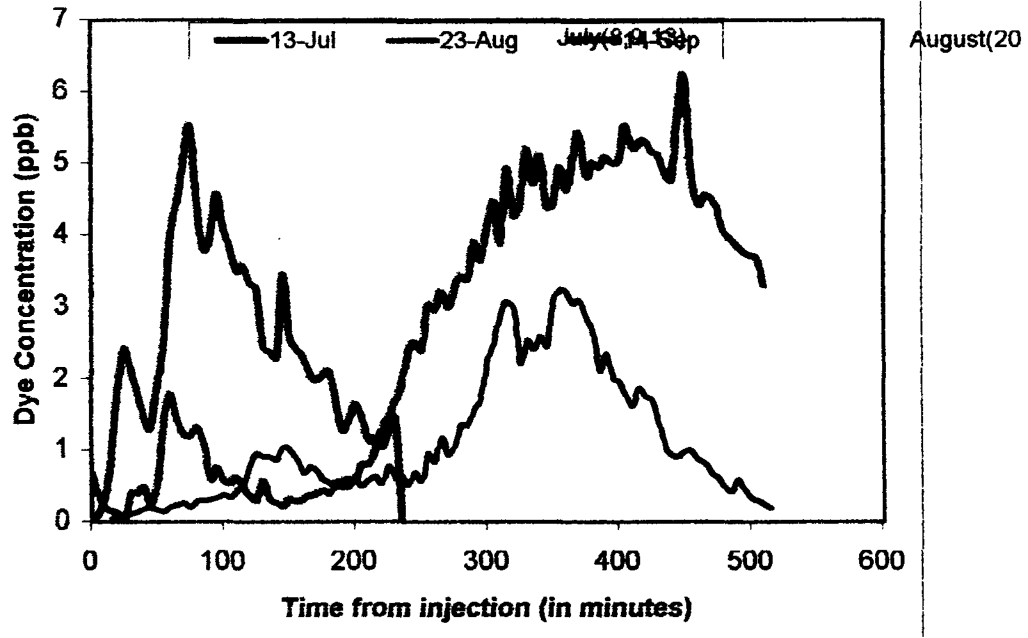
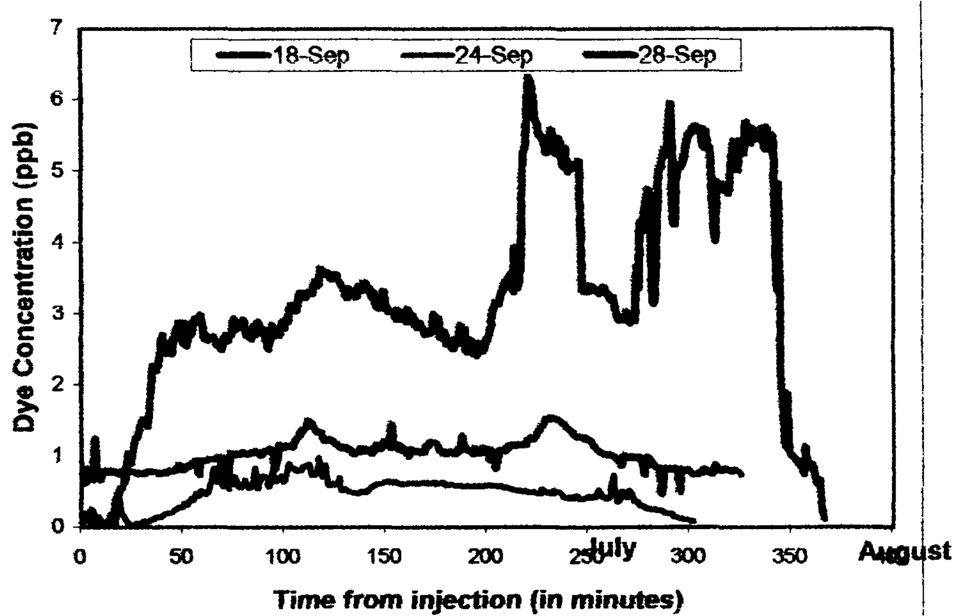


Fig. 5.45: Dye Concentration curves for J3 on 18, 24 and 28 September, 2000 at Dokriani glacier



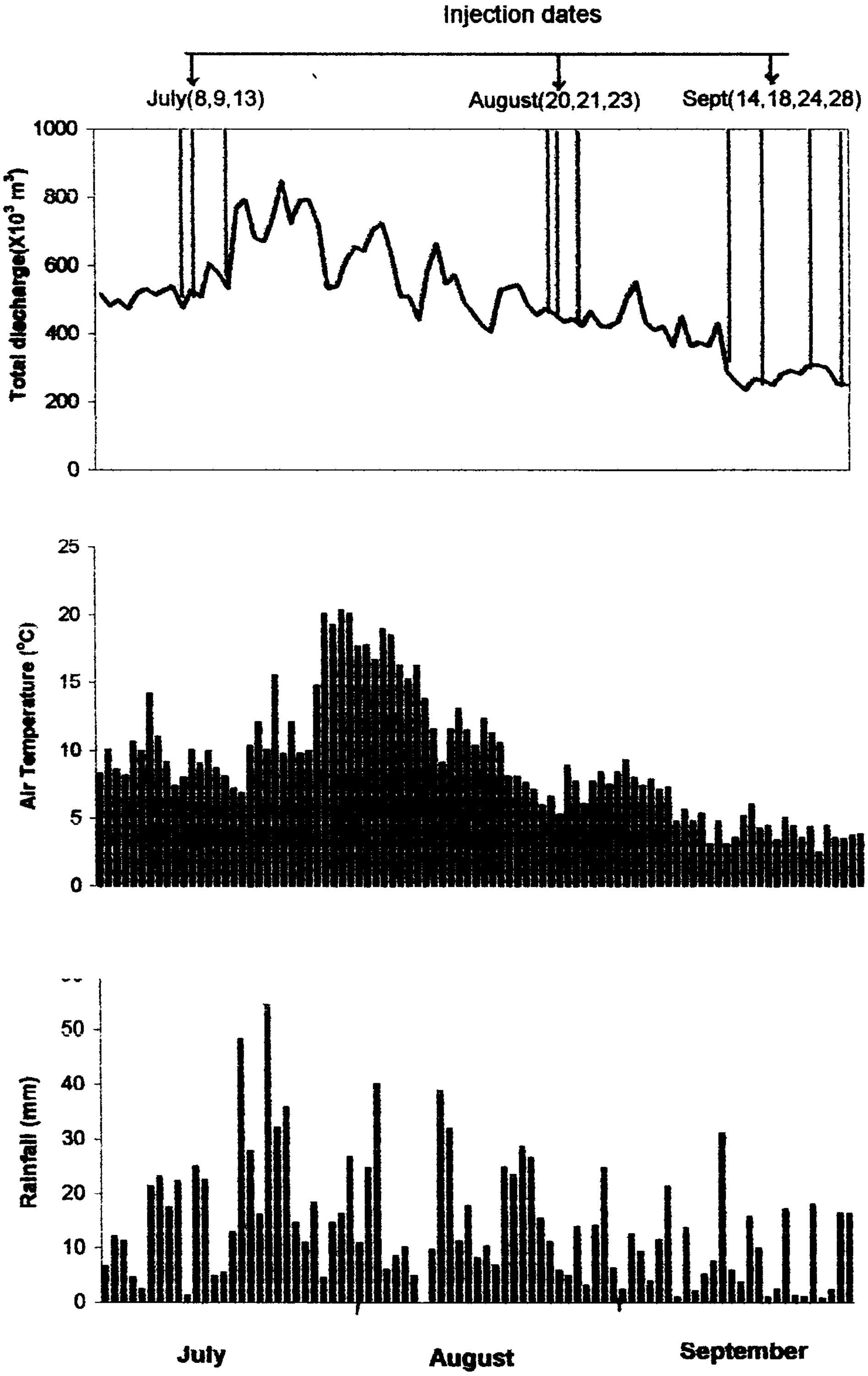


Fig.5.46: Relationship between rainfall, air temperature, discharge and injection dates

Results obtained have shown that the drainage system in the vicinity of moulins J1, J2, and J3 changed from hydraulically efficient channelised system in July to a hydraulically inefficient system during August and September. Transition from a channelised to distributed system at the glacier bed would occur spontaneously at a low water flux. Such a transition could thus be triggered by a reduction in discharge through the subglacial channel (Kamb, 1987).

Hydraulic conditions in tributaries leading from moulins to major conduits are probably unrelated to snout discharge but reflect the input to the moulin (Collins, 1995). Over the Dokriani glacier, monsoonal cloud cover reduces the radiation input and thus lowers the glacier icemelt (Hasnain, 1999). Water derived from rainfall at heavily crevassed upper region of the glacier mixes with supraglacial meltwater and delivers many low discharge inputs to the subglacial system (Nienow et al., 1998). These inputs late in the ablation season perhaps destabilize the channelised system and give rise to an enlarged network of a distributed drainage system. However the double-peaked dye concentration curves resulting from the experiment on 23 August, 18 and 24 September at moulin 3 suggest that, on these days water was drained to the snout via both channelised and distributed drainage paths (Nienow, et al., 1996 b). Furthermore experiment conducted on September 28, late in the ablation season, resulted in a dye concentration curve typical of a channelised system. These results therefore suggested that during the monsoonal rainfall period moulin J3 was switching between channelised and distributed system.

Fujita and Ageta (2000) have pointed that warming in the monsoon climate causes a decrease in accumulation and drastic increase in ablation in combination with surface albedo lowering. Hence the thinning of Dokriani glacier reduces the effect of the overburden pressure of ice (Fountain and Vauhan, 1995). This perhaps may be one of the factors, which causes rapid changes in the subglacial morphology. Therefore, it is evident that change in discharge reflects the change in the hydrological system of the glacier, which in turn is associated with the change in climatic conditions in the basin.

Chapter VI

SUMMARY AND CONCLUSION

An accurate estimation of the melt water of the glacier and total volume of water expected in the ablation season from a glacierised basin is of vital importance for planning and management of water resources including flood forecasting, reservoir operation and design of hydraulic structure etc. Limited hydrological studies have been carried out on the Himalayan glaciers because of poor accessibility, rugged terrain and harsh weather conditions. In order to study the melting behaviour of the Dokriani glacier and to investigate weather conditions around this glacier, extensive hydrological studies were carried out for the period of three years (1999-2001). Investigations were made only for summer period when active melting from glacier takes place. The following conclusions are drawn from the analysis of hydro-meteorological data collected for this study:

CHEMISTRY OF MELTWATER

The chemical analysis of meltwater revealed that Ca^{2+} is the major cation and HCO_3^- and SO_4^{2-} are the major anions. Ca^{2+} and Mg^{2+} together contribute about 55% of cations in the meltwater. Cations in the meltwater were in the decreasing order as $Ca^{2+} > Na^+ > Mg^{2+} > K^+$. Their relative contributions were 39 %, 37%, 15% and 8% in the meltwater of ablation season 1999. In the ablation seasons 2000 main emphasis were given to bicarbonate and sulphate and to understand the hydrological system of the glacier.

The average concentrations of HCO_3^- and SO_4^{2-} were found to be 0.157 meq/l and 250 meq/l respectively in the ablation season 1999. It has been observed that HCO_3^- and SO_4^{2-} follow the same trend from June to September, with only difference in their concentration.

DISCHARGE

Discharge measurements for three consecutive ablation seasons (1999-2001) near the glacier snout (600m downstream) indicated diurnal and seasonal variations with mean seasonal discharge of 3.41 $m^3 s^{-1}$, 5.40 $m^3 s^{-1}$ and 2.92 $m^3 s^{-1}$ for the years 1999, 2000 and 2001 respectively. The peak discharge period varied for the different years. The peak discharges observed were 4.10 $m^3 s^{-1}$, 7.10 $m^3 s^{-1}$ and 3.21 $m^3 s^{-1}$ for the ablation season 1999, 2000 and 2001. Most of the peak discharges in the stream have been found to be closely related with the rainfall in the region. The results showed an average daily contribution of 345 x 10^3 m^3 in the stream as runoff from the glacier in the year 1999. The mean daily contribution of discharge were $140x10^3m^3$, $260x10^3m^3$, $526x10^3m^3$ and $450x10^3$ m^3 respectively for the months of June, July, August and September, accounting for 6%, 18%, 43% and 33% of the total volume in a day in the ablation season 1999. For the ablation season 2000 and 2001, the mean daily discharge estimated was $485x10^3m^3$ and $240x10^3m^3$ respectively. For the ablation season as a whole the average values of discharges for the ablation seasons 1999-2001 have been computed as $310x10^5m^3$, $436x10^5m^3$, $288x10^5m^3$ respectively. July and August together contribute 60% of the total discharge by the Dokriani glacier, which is further supported by the high rainfall in these months.

SUSPENDED SEDIMENT

Suspended sediment load was observed during ablation months of June, July, August and September. Maximum sediment load was observed in the months of July and August that coincides with heavy monsoonal rainfall. Mean monthly values of suspended sediment for the month of June, July, August and September were 22.5 mg/l, 86.0 mg/l, 228.0 mg/l and 108.0 mg/l for ablation season 1999 and 202.7 mg/l, 106.0 mg/l and 80.0 mg/l for the month of July, August and September 2000. The mean sediment concentration was 112.0 mg/l and 130.0 mg/l for the ablation season 1999 and 2000 respectively. Average total suspended sediment transported in the ablation season 1999 and 2000 has been computed as 393 tons/km^2/month, 3658 tons/km^2/month, 6086 tons/km^2/month and 3875 tons/km^2/month for June, July, August and September 1999 and 8240 tons/km^2/month, 6490 tons/km^2/month and 3980 tons/km^2/month for July, August and September 2000 respectively. On average suspended sediment transported during the ablation seasons 1999-2000 has been computed as 16862 tons/km^2/yr. The increased sediment in the year 2000 compared to 1999 is because of increased rain intensity. The maximum sediment load from the Dokriani glacier basin was observed in the month of August. It is an established fact that amount and intensity of rainfall contributes to higher amount of sediment load in the meltwater; landslides also contribute to sediment concentration and magnitude in these streams.

METEOROLOGICAL PARAMETERS

The amount of rainfall recorded in the ablation seasons of 1999, 2000 and 2001 was 630 mm, 1279 mm and 542 mm respectively. No rainfall has been recorded in the month of June 1999 while 90 mm of rainfall has been recorded in June 2001. July and August experience maximum rainfall in the region. This has its influence on increasing discharge accompanied by increased sediment load in the respective months.

Although very poor correlation has been found between rainfall and discharge for the month of June, it improves for the months of July, August and September. Average daily rainfall component to the total glacier runoff for the ablation season 1999 was observed to be 75 x 10^3 m^3. For the melt season 2000 and 2001 this component was observed to be 95 x 10^3 m^3 and 45 x 10^3 m3 respectively. On an average monsoonal rainfall contribution was 11%, 15% and 14% of the total glacier runoff for the ablation seasons 1999, 2000 and 2001 respectively and snow/ice melt contributes 89%, 85% and 86% of total glacier runoff in 1999, 2000 and 2001.

GLACIER HYDROLOGICAL SYSTEM AND ITS RELATIONSHIP WITH DISCHARGE

Subglacial hydrological studies conducted in the year 2000 using dye tracer technique on three moulins (J1, J2 and J3) have established that internal drainage system of the glacier changes from efficient trunk channel system in the beginning of July to inefficiently distributed system in the late ablation period.

During month of July dye injection curves obtained are indicative of flow through a channelised drainage system, while the tests conducted during August showed drainage well developed, distributed system. The results obtained during September in Moulin J3 indicated that the flow progressively changed from distributed to channelised system as the flow-through velocity increased to 0.39 m s^{1-} and dispersivity reduced to 130 m on 28 September. The overall results suggest that the high discharges between 8 July and 15 August, probably resulted in the expansion of the distributed system to accommodate increased runoff. In September, however the distributed system appears to be shrinked and giving way to channelised system.

It has been concluded from the study that glaciers are very powerful agents of erosion and contribute substantial amount of sediment as well as solute to the river system. Hence better understanding of hydrological responses of glaciated catchment is necessary for formulation of efficient water resource management programmes. This study tried to find out the complicated processes operating in the glacial environment, which ultimately influence life in the plains. The results obtained in this study have shown that the water levels sustained by mighty Himalayan rivers are the consequences of the water discharge from the glaciers. Huge sediment load generated by glacial meltwater is transported to the northern Indian plains by glacier fed river. Relationship between meteorological parameters and glacier basin has been established. The study of seasonal and diurnal variations in suspended sediment concentration in the river is useful in planning of construction of dams and reservoirs for irrigation and hydropower generation.

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APPENDICES

Appendix I

Hourly discharge (m3/s) observed on different dates in 1999

Hrs	15-Jul	30-Jul	15-Aug	30-Aug	1-Sep
7:00	1.97	2.45	6.81	6.12	5.42
8:00	1.92	2.40	6.70	6.15	5.05
9:00	1.88	2.61	6.92	6.30	4.58
10:00	2.02	2.50	6.88	6.56	6.00
11:00	2.00	2.98	7.05	7.52	5.85
12:00	2.29	3.16	7.00	7.40	5.55
13:00	2.29	3.53	7.14	8.16	6.65
14:00	2.55	3.39	6.00	8.02	5.98
15:00	2.55	3.58	6.62	8.14	5.20
16:00	2.68	3.26	6.85	7.45	4.48
17:00	2.08	4.00	6.50	7.18	5.64
18:00	1.96	3.12	4.63	7.25	6.00
19:00	1.80	3.22	6.14	7.40	4.63
20:00	1.70	2.08	6.20	7.32	4.69
21:00	1.91	2.15	6.25	7.55	4.00
22:00	1.85	1.98	6.30	7.10	6.01
23:00	1.98	2.17	6.34	6.88	4.25
0:00	1.75	2.45	5.75	6.56	4.44
1:00	2.11	2.60	6.05	6.48	5.12
2:00	1.94	2.62	6.43	5.85	3.67
3:00	1.85	2.38	6.56	6.00	3.98
4:00	2.19	2.65	5.79	5.79	3.33
5:00	2.25	2.56	5.76	5.76	4.12
6:00	1.78	2.65	5.25	5.64	3.25

Appendix I

Hourly discharge (m3/s) observed on different dates in 2000

	15-Jul		30-Jul		15-Aug		30-Aug	
Hrs	**Discharge**	**EC**	**Discharge**	**EC**	**Discharge**	**EC**	**Discharge**	**EC**
	(m^3/s)	(uS/cm)	(m^3/s)	(uS/cm)	(m^3/s)	(uS/cm)	(m^3/s)	(uS/cm)
7:00	4.5	28.8	5.0	38.8	4.4	33.5	3.7	40.2
8:00	5.3	30.2	4.5	30.5	4.4	33.5	4.1	44.5
9:00	4.6	30.4	4.1	29.6	4.1	31.6	4.2	46.0
10:00	4.5	25.6	2.7	28.0	4.3	24.8	4.9	48.0
11:00	5.3	28.0	6.1	22.0	5.1	26.5	4.5	46.0
12:00	5.8	22.0	6.7	19.5	5.3	15.0	4.5	42.3
13:00	5.8	18.0	6.1	14.0	5.2	14.8	5.4	36.7
14:00	6.0	19.0	6.1	23.0	6.0	22.5	5.1	30.5
15:00	6.1	16.0	7.3	19.0	5.8	23.8	4.5	30.0
16:00	5.4	15.0	7.0	20.0	6.1	25.0	4.9	30.0
17:00	6.0	17.8	6.8	25.0	5.8	23.0	4.3	27.0
18:00	5.6	15.0	6.5	17.5	4.6	24.8	3.5	38.0
19:00	4.4	20.0	7.1	16.0	4.3	25.9	3.6	29.2
20:00	4.1	18.0	6.4	16.3	3.6	25.5	4.0	27.4
21:00	5.0	22.0	4.5	20.5	3.8	28.0	4.9	30.0
22:00	3.8	29.0	4.9	21.0	3.1	26.0	4.6	34.0
23:00	3.3	30.0	4.5	22.0	3.6	25.5	3.3	38.0
0:00	3.4	28.0	3.8	22.6	3.4	27.4	3.0	38.0
1:00	3.7	32.0	3.9	31.0	3.7	22.9	3.0	41.0
2:00	4.5	18.0	4.0	30.2	3.1	30.3	4.4	38.2
3:00	4.3	26.0	5.3	19.0	3.2	30.9	4.5	33.5
4:00	4.0	22.9	4.5	22.0	4.5	25.0	3.1	28.6
5:00	3.9	30.5	5.1	16.0	3.4	32.0	3.6	20.0
6:00	5.2	19.0	6.4	14.0	4.5	29.1	4.1	38.0

Appendix I

Hourly discharge (m3/s) observed on different dates in 2001

Date	Decijulian	Time (Hrs)	Discharge (m^{3}s^{-1})	Air T (°C)	Water T (°C)	EC (uS/cm)	pH	Bicarbon. (meq/l)
16-Jul	197.33	8.00	2.84	11.6	2.3	2.7	7.1	0.06
	197.38	9.00	2.90	9.9	2.5	2.7	7.1	0.06
	197.42	10.00	3.05	10.4	2.4	2.7	7.1	0.07
	197.46	11.00	3.52	8.6	2.5	2.5	7.1	0.07
	197.50	12.00	3.05	8.4	2.5	2.4	7.1	0.09
	197.54	13.00	3.85	11.3	2.5	2.3	7.1	0.11
	197.58	14.00	3.67	10.7	2.5	2.3	7.1	0.11
	197.63	15.00	3.69	9.3	2.5	2.3	7.1	0.11
	197.67	16.00	4.03	10.5	2.5	2.4	7.1	0.09
	197.71	17.00	4.01	12.6	2.5	2.4	7.1	0.09
	197.75	18.00	3.70	10.3	2.2	2.4	7.1	0.09
	197.79	19.00	3.38	9.2	2.4	2.5	7.1	0.09
	197.83	20.00	3.37	8.5	2.4	2.5	7.1	0.09
	197.88	21.00	3.43	9.3	2.5	2.6	7.1	0.09
	197.92	22.00	3.01	9.9	2.5	2.7	7.1	0.06
	197.96	23.00	3.26	9.7	2.5	2.8	7.1	0.05
	198.00	24.00	3.00	9.1	2.6	2.9	7.1	0.05
17-Jul	198.04	1.00	3.59	9.2	2.6	2.8	7.1	0.05
	198.08	2.00	3.65	9.4	2.5	2.9	7.1	0.05
	198.13	3.00	2.98	9.7	2.8	2.7	7.1	0.07
	198.17	4.00	2.79	9.5	2.5	2.9	7.1	0.11
	198.21	5.00	2.85	8.8	2.6	3.0	7.1	0.07
	198.25	6.00	2.82	7.8	2.5	3.1	7.1	0.06
	198.29	7.00	2.82	8.7	2.6	3.1	7.2	0.05
1-Aug	213.33	8.00	3.03	14.6	2.4	3.0	7.7	0.106
	213.38	9.00	3.26	19.8	2.5	3.0	7.7	0.106
	213.42	10.00	3.66	21.0	2.8	2.8	7.9	0.143
	213.46	11.00	3.58	19.3	2.4	2.5	7.8	0.164
	213.50	12.00	3.89	20.8	2.4	2.2	7.5	0.186
	213.54	13.00	2.40	28.0	2.8	1.8	7.5	0.210
	213.58	14.00	3.69	24.3	3.0	2.4	7.6	0.263
	213.63	15.00	4.49	20.4	2.9	1.8	7.6	0.236
	213.67	16.00	4.36	22.2	2.8	1.8	7.6	0.186
	213.71	17.00	5.22	11.7	1.8	1.7	7.8	0.164
	213.75	18.00	3.85	16.4	2.4	1.7	7.8	0.164
	213.79	19.00	3.70	15.9	2.2	1.8	7.7	0.143
	213.83	20.00	3.50	12.5	2.3	1.6	7.6	0.236
	213.88	21.00	3.76	12.6	2.5	1.6	7.6	0.143
	213.92	22.00	3.38	14.3	2.4	1.8	7.6	0.143
	213.96	23.00	3.33	15.6	2.5	1.8	7.5	0.124
	214.00	24.00	3.36	9.9	2.4	1.8	7.5	0.124
2-Aug	214.04	1.00	3.03	10.2	2.3	1.8	7.5	0.124
	214.08	2.00	3.25	10.5	2.5	1.7	7.5	0.124
	214.13	3.00	2.97	9.4	2.5	1.7	7.5	0.143
	214.17	4.00	2.91	11.4	2.6	1.7	7.5	0.124
	214.21	5.00	2.91	11.0	2.5	1.6	7.4	0.164
	214.25	6.00	2.87	9.1	2.4	1.6	7.4	0.164
	214.29	7.00	2.84	7.7	2.4	2.4	7.4	0.143
	214.33	8.00		18.8	2.7	2.8	7.5	0.143

Appendix I

Hourly discharge (m3/s) observed on different dates in 2001

Date	Decijulian	Time (Hrs)	Discharge (m^{3}s^{-1})	Air T (°C)	Water T (°C)	EC (uS/cm)	pH	Bicarbon. (meq/l)
16-Aug	228.33	8.00	2.99	15.5	2.5	6.3	6.9	0.143
	228.38	9.00	2.90	18.3	2.5	5.0	7.0	0.143
	228.42	10.00	3.11	22.2	3.2	5.8	7.2	0.164
	228.46	11.00	3.74	28.8	3.3	5.7	7.2	0.164
	228.50	12.00	4.83	25.8	2.9	4.1	7.2	0.186
	228.54	13.00	3.45	17.9	3.1	3.4	7.1	0.210
	228.58	14.00	3.87	13.8	2.8	3.4	7.1	0.236
	228.63	15.00	4.80	18.5	3.0	3.4	7.2	0.292
	228.67	16.00	4.99	14.5	2.9	4.8	7.5	0.236
	228.71	17.00	5.66	16.2	2.9	4.5	8.0	0.210
	228.75	18.00	4.96	13.4	2.8	3.2	7.8	0.210
	228.79	19.00	4.27	12.8	2.8	3.2	7.7	0.186
	228.83	20.00	4.02	12.7	2.8	3.6	7.6	0.143
	228.88	21.00	3.90	12.8	2.8	6.2	7.4	0.143
	228.92	22.00	3.57	12.1	2.8	3.8	7.5	0.143
	228.96	23.00	3.95	11.9	2.8	4.0	7.6	0.143
	229.00	24.00	3.50	11.8	2.9	7.5	7.6	0.106
17-Aug	229.04	1.00	3.60	10.5	2.9	4.0	7.5	0.106
	229.08	2.00	3.92	11.4	2.9	5.5	7.3	0.106
	229.13	3.00	3.25	10.3	3.0	4.2	7.3	0.106
	229.17	4.00	3.02	9.8	2.9	7.6	7.3	0.124
	229.21	5.00	2.93	9.6	2.9	5.5	7.4	0.124
	229.25	6.00	2.97	8.8	2.9	4.4	7.4	0.143
	229.29	7.00	2.97	7.7	3.1	4.1	7.3	0.143
	229.33	8.00	2.82	11.7	3.3	4.2	7.1	0.143
1-Sep	244.33	8:00	3.58	12.5	2.6	3.4	6.70	0.124
	244.38	9:00	3.60	12.4	2.6	3.8	6.75	0.124
	244.42	10:00	3.26	13.0	2.4	4.8	6.80	0.143
	244.46	11:00	3.26	9.8	2.3	4.3	6.85	0.164
	244.50	12:00	2.20	10.4	2.4	3.8	6.88	0.186
	244.54	13:00	2.83	12.2	2.3	3.3	6.90	0.210
	244.58	14:00	3.26	12.3	2.3	3.1	6.95	0.263
	244.63	15:00	2.00	10.2	2.3	3.0	6.96	0.210
	244.67	16:00	2.89	11.8	2.2	3.7	6.92	0.164
	244.71	17:00	3.60	12.0	2.4	3.2	7.01	0.143
	244.75	18:00	3.60	12.2	2.1	3.6	7.02	0.124
	244.79	19:00	2.49	12.2	1.9	3.6	7.00	0.124
	244.83	20:00	4.26	7.5	1.9	3.4	6.96	0.124
	244.88	21:00	2.71	7.5	1.9	3.1	7.00	0.124
	244.92	22:00	3.00	7.2	1.8	2.8	7.02	0.106
	244.96	23:00	2.10	5.0	1.8	2.2	7.02	0.106
	245.00	0:00	2.29	5.2	1.7	2.2	7.04	0.090
2-Sep	245.04	1:00	2.83	4.8	1.6	2.1	7.04	0.090
	245.08	2:00	2.99	4.7	1.1	2.1	6.97	0.090
	245.13	3:00	2.88	2.5	0.9	2.1	6.95	0.090
	245.17	4:00	2.96	2.5	0.9	1.9	6.90	0.106
	245.21	5:00	2.39	1.9	0.8	1.8	6.90	0.106
	245.25	6:00	2.32	2.3	0.2	2.4	6.86	0.124
	245.29	7:00	2.30	8.4	0.9	2.5	6.78	0.124
	245.33	8:00	2.12	11.2	2.8	2.9	6.61	0.124

Appendix II

Dye tracer experiment for moulin 1 (J1)

08/07/2000(J1)				20/08/2000(J1)			
Time(min)	(ppb)	Time(min)	(ppb)	Time(min)	(ppb)	Time(min)	(ppb)
2	0.131	68	0.404	10	0.035	170	0.968
4	0.208	70	0.197	15	0.048	175	0.982
6	0.371	72	0.410	20	0.056	180	0.900
8	0.587	74	0.288	25	0.098	185	0.825
10	0.699	76	0.413	30	0.156	190	0.807
12	0.805	78	0.274	35	0.167	195	0.737
14	0.888	80	0.258	40	0.162	200	0.690
16	0.886	82	0.193	45	0.169	205	0.676
18	0.817	84	0.179	50	0.226	210	0.732
20	0.861	86	0.193	55	0.275	215	0.682
22	0.957	88	0.069	60	0.384	220	0.610
24	1.020	90	0.187	65	0.387	225	0.511
26	1.220	92	0.408	70	0.419	230	0.394
28	1.370	94	0.334	75	0.494	235	0.297
30	1.490	96	0.317	80	0.440	240	0.136
32	1.560	98	0.503	85	0.469	245	0.037
34	1.650	100	0.447	90	0.482	250	0.008
36	1.670	102	0.536	95	0.596		
38	1.570	104	0.414	100	0.609		
40	1.450	106	0.678	105	0.518		
42	1.470	108	0.447	110	0.543		
44	1.440	110	0.367	115	0.558		
46	1.290	112	0.308	120	0.627		
48	1.350	114	0.536	125	0.701		
50	1.180	116	0.196	130	0.878		
52	1.060	118	0.142	135	0.749		
54	1.100	120	0.257	140	0.737		
56	0.887	122	0.359	145	0.786		
58	0.734	124	0.414	150	0.855		
60	0.694	126	0.193	155	0.852		
62	0.579	128	0.165	160	0.841		
64	0.467	130	0.093	165	0.936		
66	0.456						

Dye tracer experiment for moulin 2 (J2)

9 July, 2000 (J2)				21 August 2000(J2)					
(min)	(ppb)	(min)	(ppb)	(min)	(ppb)	(min)	(ppb)	(min)	(ppb)
6	0.053	126	0.257	10	0.000	155	0.310	305	0.516
10	0.126	130	0.269	15	0.000	160	0.318	310	0.473
14	0.159	134	0.248	20	0.051	165	0.324	315	0.501
18	0.173	138	0.221	25	0.085	170	0.340	320	0.440
22	0.155	142	0.187	30	0.129	175	0.328	325	0.416
26	0.199	146	0.137	35	0.155	180	0.303	330	0.405
30	0.188	150	0.140	40	0.178	185	0.324	335	0.389
34	0.199	154	0.109	45	0.182	190	0.327	340	0.360
38	0.200	158	0.067	50	0.196	195	0.330	345	0.351
42	0.213	162	0.071	55	0.201	200	0.344	350	0.370
46	0.262	166	0.077	60	0.218	205	0.359	355	0.372
50	0.278	170	0.078	65	0.186	210	0.401	360	0.365
54	0.275	174	0.048	70	0.172	215	0.395	365	0.398
58	0.273	178	0.030	75	0.190	220	0.472	370	0.371
62	0.263	182	0.028	80	0.265	225	0.455	375	0.380
66	0.288	186	0.030	85	0.211	230	0.448	380	0.328
70	0.322	190	0.007	90	0.237	235	0.468	385	0.310
74	0.343	194	0.004	95	0.288	240	0.456	390	0.262
78	0.343			100	0.361	245	0.511	395	0.287
82	0.348			105	0.336	250	0.561	400	0.242
86	0.340			110	0.295	255	0.579	405	0.246
90	0.342			115	0.303	260	0.550	410	0.248
94	0.324			120	0.352	265	0.546	415	0.267
98	0.300			125	0.399	270	0.577	420	0.286
102	0.293			130	0.371	275	0.613	425	0.254
106	0.319			135	0.402	280	0.609	430	0.206
110	0.293			140	0.368	285	0.600	435	0.188
114	0.286			145	0.350	290	0.581	440	0.140
118	0.279			150	0.331	295	0.574	445	0.114
122	0.289			155	0.310	300	0.566		

Appendix II

Dye tracer experiment for moulin 3 (J3)

9 July, 2000 (J2)				21 August 2000(J2)					
(min)	(ppb)	(min)	(ppb)	(min)	(ppb)	(min)	(ppb)	(min)	(ppb)
6	0.053	126	0.257	10	0.000	155	0.310	305	0.516
10	0.126	130	0.269	15	0.000	160	0.318	310	0.473
14	0.159	134	0.248	20	0.051	165	0.324	315	0.501
18	0.173	138	0.221	25	0.085	170	0.340	320	0.440
22	0.155	142	0.187	30	0.129	175	0.328	325	0.416
26	0.199	146	0.137	35	0.155	180	0.303	330	0.405
30	0.188	150	0.140	40	0.178	185	0.324	335	0.389
34	0.199	154	0.109	45	0.182	190	0.327	340	0.360
38	0.200	158	0.067	50	0.196	195	0.330	345	0.351
42	0.213	162	0.071	55	0.201	200	0.344	350	0.370
46	0.262	166	0.077	60	0.218	205	0.359	355	0.372
50	0.278	170	0.078	65	0.186	210	0.401	360	0.365
54	0.275	174	0.048	70	0.172	215	0.395	365	0.398
58	0.273	178	0.030	75	0.190	220	0.472	370	0.371
62	0.263	182	0.028	80	0.265	225	0.455	375	0.380
66	0.288	186	0.030	85	0.211	230	0.448	380	0.328
70	0.322	190	0.007	90	0.237	235	0.468	385	0.310
74	0.343	194	0.004	95	0.288	240	0.456	390	0.262
78	0.343			100	0.361	245	0.511	395	0.287
82	0.348			105	0.336	250	0.561	400	0.242
86	0.340			110	0.295	255	0.579	405	0.246
90	0.342			115	0.303	260	0.550	410	0.248
94	0.324			120	0.352	265	0.546	415	0.267
98	0.300			125	0.399	270	0.577	420	0.286
102	0.293			130	0.371	275	0.613	425	0.254
106	0.319			135	0.402	280	0.609	430	0.206
110	0.293			140	0.368	285	0.600	435	0.188
114	0.286			145	0.350	290	0.581	440	0.140
118	0.279			150	0.331	295	0.574	445	0.114
122	0.289			155	0.310	300	0.566		

Dye tracer experiments conducted on Moulin J3 (13July, 23Aug, 14Sept)

13-Jul-00		23-Aug-00				14-Sep-00			
(min)	(ppb)	(min)	(ppb)	(min)	(ppb)	(min)	(ppb)	(min)	(ppb)
5	0.100	15	0.038	270	0.937	15	0.400	265	3.430
10	0.375	20	0.086	275	1.070	20	0.400	270	3.380
15	0.950	25	0.102	280	1.350	25	0.490	275	3.900
20	1.875	30	0.114	285	1.360	30	0.237	280	3.650
25	2.425	35	0.138	290	1.590	35	0.569	285	3.986
30	2.075	40	0.185	295	1.730	40	1.400	290	4.470
35	1.800	45	0.196	300	2.280	45	1.780	295	3.890
40	1.450	50	0.172	305	2.540	50	1.400	300	4.930
45	1.300	55	0.140	310	2.910	55	1.220	305	4.270
50	1.950	60	0.216	315	3.080	60	1.200	310	4.470
55	2.600	65	0.242	320	2.960	65	1.320	315	5.200
60	3.950	70	0.266	325	2.220	70	1.100	320	4.720
65	4.500	75	0.204	330	2.540	75	0.592	325	5.120
70	5.075	80	0.289	335	2.410	80	0.764	330	4.390
75	5.525	85	0.301	340	2.590	85	0.570	335	4.430
80	4.475	90	0.321	345	2.470	90	0.552	340	4.940
85	3.800	95	0.343	350	3.060	95	0.625	345	4.620
90	3.950	100	0.382	355	3.250	100	0.482	350	5.030
95	4.575	105	0.342	360	3.200	105	0.364	355	5.430
100	4.100	110	0.454	365	3.050	110	0.298	360	4.830
105	3.825	115	0.503	370	3.090	115	0.579	365	5.000
110	3.500	120	0.828	375	2.840	120	0.331	370	4.940
115	3.575	125	0.961	380	2.650	125	0.267	375	5.080
120	3.325	130	0.914	385	2.120	130	0.223	380	5.000
125	3.250	135	0.918	390	2.350	135	0.320	385	5.020
130	2.450	140	0.882	395	2.020	140	0.284	390	5.540
135	2.375	145	1.050	400	1.960	145	0.320	395	5.220
140	2.300	150	1.020	405	1.790	150	0.366	400	5.270
145	3.450	155	0.885	410	1.620	155	0.382	405	5.310
150	2.600	160	0.694	415	1.870	160	0.456	410	5.160
155	2.400	165	0.772	420	1.760	165	0.402	415	5.110
160	2.300	170	0.725	425	1.700	170	0.537	420	4.830
165	2.075	175	0.599	430	1.380	175	0.562	425	4.770
170	1.975	180	0.560	435	1.060	180	0.599	430	5.630
175	2.050	185	0.508	440	0.944	185	0.586	435	6.210
180	2.100	190	0.486	445	0.917	190	0.801	440	4.830
185	1.700	195	0.500	450	0.985	195	0.809	445	4.430
190	1.275	200	0.592	455	0.993	200	1.030	450	4.540
195	1.425	205	0.506	460	0.876	205	1.300	455	4.510
200	1.650	210	0.595	465	0.812	210	1.440	460	4.330
205	1.450	215	0.640	470	0.685	215	1.690	465	4.050
210	1.125	220	0.541	475	0.622	220	1.930	470	3.950
215	1.175	225	0.780	480	0.509	225	2.380	475	3.840
220	1.050	230	0.620	485	0.438	230	2.510	480	3.760
225	1.250	235	0.640	490	0.592	235	2.400	485	3.710
230	1.450	240	0.527	495	0.464	240	3.030	490	3.670

Appendix II

Dye tracer experiments conducted on Moulin J3 (September 18, 2000)

Time in minutes	Conc. in ppb	Time in minutes	Conc. in ppb	Time in minutes	Conc. in ppb	Time in minutes	Conc. in ppb
1	0.09	41	2.50	81	2.71	171	2.72
2	0.20	42	2.45	82	2.77	172	2.74
3	0.14	43	2.58	83	2.73	173	2.86
4	0.10	44	2.46	84	2.65	174	3.00
5	0.25	45	2.45	85	2.83	175	2.75
6	0.20	46	2.73	86	2.71	176	2.94
7	0.05	47	2.79	87	2.90	177	2.68
8	0.03	48	2.87	88	2.79	178	2.72
9	0.14	49	2.81	89	2.80	179	2.75
10	0.01	50	2.59	90	2.73	180	2.57
11	0.02	51	2.87	91	2.65	181	2.64
12	0.04	52	2.54	92	2.51	182	2.62
13	0.04	53	2.69	93	2.60	183	2.52
14	0.10	54	2.70	94	2.85	184	2.52
15	0.18	55	2.85	95	2.69	185	2.65
16	0.20	56	2.93	96	2.79	186	2.64
17	0.39	57	2.90	97	2.72	187	2.85
18	0.44	58	2.90	98	2.70	188	2.59
19	0.54	59	2.98	99	2.89	189	2.79
20	0.55	60	2.69	100	2.80	190	2.47
21	0.62	61	2.70	151	3.03	191	2.57
22	0.80	62	2.62	152	3.03	192	2.63
23	1.04	63	2.67	153	3.04	193	2.44
24	0.90	64	2.65	154	3.01	194	2.60
25	1.00	65	2.69	155	2.93	195	2.41
26	1.15	66	2.63	156	3.06	196	2.60
27	1.25	67	2.55	157	2.93	197	2.50
28	1.27	68	2.60	158	3.02	198	2.47
29	1.44	69	2.49	159	3.00	199	2.51
30	1.49	70	2.54	160	2.89	200	2.62
31	1.52	71	2.70	161	3.08	201	2.69
32	1.48	72	2.62	162	2.89	202	2.83
33	1.42	73	2.70	163	2.99	203	3.03
34	1.73	74	2.71	164	2.94	204	3.15
35	2.27	75	2.94	165	2.81	205	3.15
36	2.20	76	2.78	166	2.88	206	3.14
37	2.21	77	2.89	167	2.86	207	3.29
38	2.28	78	2.85	168	2.80	208	3.33
39	2.42	79	2.84	169	2.73	209	3.43
40	2.71	80	2.92	170	2.71	210	3.43

Appendix II

Dye tracer experiments conducted on Moulin J3 (September 24, 2000)

Time in minutes	Conc. in ppb	Time in minutes	Conc. in ppb	Time in minutes	Conc. in ppb	Time in minutes	Conc. in ppb
1	0.019	41	0.186	81	0.615	121	0.648
2	0.012	42	0.194	82	0.586	122	0.592
3	0.003	43	0.196	83	0.559	123	0.620
4	0.004	44	0.207	84	0.593	124	0.597
5	0.003	45	0.216	85	0.847	125	0.611
6	0.010	46	0.246	86	0.625	126	0.611
7	0.014	47	0.270	87	0.551	127	0.700
8	0.020	48	0.286	88	0.679	128	0.537
9	0.030	49	0.287	89	0.732	129	0.546
10	0.024	50	0.293	90	0.722	130	0.542
11	0.013	51	0.335	91	0.702	131	0.518
12	0.037	52	0.323	92	0.578	132	0.503
13	0.035	53	0.365	93	0.610	133	0.499
14	0.054	54	0.407	94	0.816	134	0.488
15	0.064	55	0.393	95	0.661	135	0.493
16	0.082	56	0.474	96	0.652	136	0.483
17	0.076	57	0.446	97	0.707	137	0.488
18	0.360	58	0.453	98	0.732	138	0.504
19	0.386	59	0.518	99	0.677	139	0.497
20	0.197	60	0.476	100	0.654	140	0.497
21	0.166	61	0.469	101	0.801	141	0.528
22	0.100	62	0.493	102	0.899	142	0.544
23	0.070	63	0.540	103	0.848	143	0.572
24	0.046	64	0.670	104	0.837	144	0.586
25	0.032	65	0.833	105	0.818	145	0.601
26	0.024	66	0.657	106	0.797	146	0.610
27	0.052	67	0.649	107	0.813	147	0.615
28	0.052	68	0.912	108	0.812	148	0.626
29	0.045	69	0.666	109	0.850	149	0.638
30	0.061	70	0.575	110	0.860	150	0.646
31	0.090	71	0.728	111	0.880	151	0.643
32	0.071	72	0.726	112	0.890	152	0.648
33	0.089	73	0.672	113	0.749	153	0.634
34	0.100	74	0.612	114	0.737	154	0.658
35	0.111	75	0.722	115	0.757	155	0.643
36	0.114	76	0.680	116	0.859	156	0.629
37	0.144	77	0.607	117	0.976	157	0.625
38	0.140	78	0.582	118	0.730	158	0.620
39	0.143	79	0.579	119	0.771	159	0.614
40	0.149	80	0.680	120	0.882	160	0.621

Dye tracer experiments conducted on Moulin J3 (September 28, 2000)

Time in minutes	Conc. in ppb	Time in minutes	Conc. in ppb	Time in minutes	Conc. in ppb	Time in minutes	Conc. in ppb
1	0.63	42	0.77	83	1.05	124	1.22
2	0.63	43	0.79	84	1.05	125	1.17
3	0.83	44	0.79	85	1.06	126	1.17
4	0.75	45	0.78	86	1.07	127	1.16
5	0.67	46	0.80	87	1.06	128	1.11
6	0.83	47	0.81	88	1.01	129	1.11
7	1.25	48	0.88	89	1.04	130	1.13
8	0.75	49	0.87	90	1.07	131	1.09
9	0.67	50	0.80	91	1.07	132	1.11
10	0.75	51	0.82	92	1.07	133	1.08
11	0.78	52	0.85	93	1.09	134	1.03
12	0.80	53	0.85	94	1.09	135	1.05
13	0.78	54	0.87	95	0.89	136	1.06
14	0.77	55	0.90	96	0.84	137	1.06
15	0.79	56	0.92	97	1.14	138	1.11
16	0.78	57	0.94	98	1.16	139	1.08
17	0.78	58	0.74	99	1.12	140	1.07
18	0.75	59	0.93	100	1.14	141	1.09
19	0.77	60	0.93	101	1.15	142	1.06
20	0.79	61	0.93	102	1.15	143	1.04
21	0.80	62	0.96	103	1.13	144	1.10
22	0.80	63	0.96	104	1.14	145	1.09
23	0.78	64	0.96	105	1.19	146	1.16
24	0.78	65	0.96	106	1.23	147	1.10
25	0.78	66	0.97	107	1.26	148	1.15
26	0.77	67	0.98	108	1.32	149	1.19
27	0.76	68	0.98	109	1.36	150	1.20
28	0.75	69	0.97	110	1.40	151	1.17
29	0.76	70	0.98	111	1.44	152	1.13
30	0.75	71	0.81	112	1.50	153	1.46
31	0.76	72	0.55	113	1.46	154	1.16
32	0.77	73	1.03	114	1.46	155	1.15
33	0.78	74	1.04	115	1.39	156	1.10
34	0.77	75	1.02	116	1.33	157	1.16
35	0.78	76	1.04	117	1.33	158	1.15
36	0.78	77	1.04	118	1.34	159	1.08
37	0.77	78	1.03	119	1.28	160	1.06
38	0.75	79	1.05	120	1.21	161	1.00
39	0.76	80	1.06	121	1.23	162	1.08
40	0.76	81	1.03	122	1.22	163	1.10
41	0.76	82	1.04	123	1.24	164	1.06