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Rainfall Contribution in Bhagirathi River near Gangotri Glacier Snout, Gomukh, Western Himalayas, India, Using Stable Isotope

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ABSTRACT: Gomukh is the snout of Gangotri Glacier located at an altitude of 4000 m from where the snow/glacier meltwater stream known as Bhagirathi river emerges out. Stream and rainfall samples were collected for stable isotopes ($\delta^{18}O$ and δD) analysis during ablation period (May to October) during the years 2004, 2005 and 2006 at site Bhojwasa, 3 km downstream of Gomukh. The isotopic characteristics of stream water are used to delineate the contribution of different sources in river Bhagirathi during ablation period. The isotopic characteristics of meltwater and rainfall were used to estimate the rain water contribution to Bhagirathi river. The variation in isotopic composition ($\delta^{18}O$) with time in river water shows the varied contribution of snow/glacier and runoff component in Bhagirathi river during the ablation period of 2005. This variation is quite obvious due to change in climatic conditions. Isotopic signature of stream water shows the snow dominated melt water up to third week of June and later ice/glacier dominate in the stream discharge.The significant variation in $\delta^{18}O$ river water was observed during pre and post SW monsoon caused rain event occurred during July and September 2005. The isotopic composition of precipitation was much depleted (–30.3‰) than the stream water (–14‰ to –16‰) during the study period. Rainfall contribution to stream discharge was computed using two component model. The contribution was found maximum upto 40% of total discharge on particular rain of particular rainy day. The complete hydrograph separated out for three storm events in the months of July and September during the year 2005 revealed the rainfall contribution to the tune of 14% to 15% of the total stream discharge in each storm period. This accounts an aggregate 3% contribution of rainfall to total discharge of river Bhagirathi that occurred during ablation period of the year 2005.

INTRODUCTION

The Great Himalayas are the enormous gathering grounds of snow which feed a multitude of glaciers, some of which are among the largest in the world outside the Polar circles (Wadia, 1990). Precipitation in the form of snow occurs only during October to March, when the primary source of moisture is related to the winter monsoon and western disturbances. The accumulation is maximum when the snowline recedes to about 1500 m in the western Himalaya and to about 3000 m in the eastern Himalaya. The climate of the glaciated central Himalayan region is influenced by precipitation during the summer monsoon which develops over the Asian countries. Over India, the monsoonal rains being by mid June. The south west monsoon also plays an important role during the ablation period of Himalayan glaciers (Nizampurkar *et al.,* 2002). The snow and glacier melt runoff play a vital role in making all north Indian rivers perennial. Depending upon the prevailing climatic conditions, the runoff contribution from the glaciers in the Himalayan rivers starts in May, after depletion of accumulated seasonal snow. Usually the melt contribution from these glaciers continues till October (Singh, 2005). The snow and glacier melt to Himalayan river starts in summer months after melting of seasonal snow when the water demand increases for hydropower generation, drinking and irrigation etc. Therefore, it becomes essential to understand the melt water contribution to river on monthly basis during ablation period. Attempt has been made to study the contribution of snow and glacier melt runoff into annual flow of the different Himalayan rivers (Singh *et al.*, 1997; Singh and Jain, 2002). For the few glaciers of Himalayan region, runoff and sediment load transportation studies have been carried out by Singh *et al.* (1995, 2003, 2005), Hasnain (1996) and Hasnain and Thayyen (1999). However, the contribution of snow, glacier and rainfall is still unknown near the snout.

Other than conventional techniques, several studies using radioactive and stable isotopes have been carried out in polar and temperate regions, particularly Antarctic, Artic and Alpine regions, (Dansgaard *et al.*, 1969; Jouzel *et al.*, 1987). Studies from the India and Nepal Himalayas are relatively sparse (Yasunari 1976; Garbczak *et al.*, 1983; Nijampurkar and Bhandari, 1984; Mayewski *et al.*, 1986; Wake, 1989; Nijampurkar and Rao, 1993). Recent studies based on $\delta^{18}O$ in snow/ice and ice core from the Tibetan (Xizang) Himalaya have addressed the seasonal relationship between $\delta^{18}O$ in snow/ice and air temperature and moisture sources (Aizen *et al.*, 1996; Yao *et al.*, 1996; Thompson *et al.*, 1997). Yao *et al.* (1996) demonstrated that the $\delta^{18}O$ -T relationship has a positive slope over the northern part of Tibetan Plateau and suggest that the slope "invert" over a narrow band between the Himalaya and the central plateau to the north. However, the contribution of snow, ice and rainfall in stream discharge near the snout is still unknown. It is the first attempt through isotopic characteristic of stream meltawter, snow, ice and rainfall near the snout to study the contribution of different sources. The $\delta^{18}O$ variation in stream water is used to estimate the contribution of rainfall to stream discharge.

STUDY AREA

Gangotri glacier is the largest glacier in the western Himalayas. The study area falls in Uttarkashi District of Uttarakhand State (U.K.) between latitude 30° 43′N and 31°01′N and between longitudes 79°0′E and 79°17′E (Figure 1). The proglacial meltwater stream, known as the Bhagirathi River emerges from the snout of the Gangotri Glacier at an elevation of 4000 m. The meltwater is drained through a well defined single terminus of the glacier, known as Gomukh (the mouth of a cow). Gomukh is considered as the origin of the Ganga River. The gangotri glacier system comprising of the main Gangotri Glacier (length: 30.20 km; width: 0.2 – 2.35 km; area: 86.32 km^2) as the trunk part of the system. The major glacier tributaries of the Gangotri Glacier system are Raktvarn Glacier (area: 55.30 km^2), Chaturangi Glacier (area: 67.70 km^2), Kirti Glacier (area: 33.14 km^2), Swachand Glacier (area: 16.71 km^2), Ghanohim Glacier (area: 12.97 km^2), Meru Glacier (area: 6.11 km^2), Maindi Glacier (area: 4.76 km^2) and a few others having a glacierized area of about 3.08 km^2 in total. The total catchment area upto the sampling site is about 556 km^2, out of the total catchment area 286 km^2 is glacierized area (Singh *et al.*, 2005). Snow and glacier melt runoff play a vital role in making all north Indian rivers (including Indus and Ganga) perennial. Depending upon the prevailing climatic conditions, the runoff contribution from the snow/glaciers starts in May, after depletion of accumulated seasonal snow. Usually, the melt contribution from these glaciers continues till October. The elevation range of the Gangotri Glacier varies from 4000 to 700 m and the elevation of the study area upto the gauging site lies between 3800 and 7000 m.

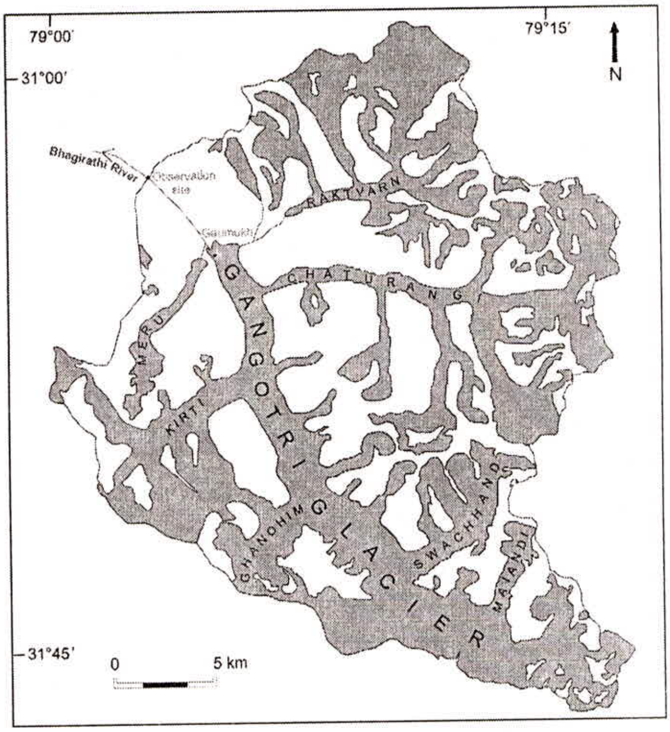

Fig. 1: Map of study area

METHODOLOGY

Integrated monthly and ten daily precipitation samples were collected during ablation period of years of 2004, 2005 and 2006 using an ordinary raingauge. From the integrated samples, 20 ml water sample was collected for stable isotopes and 500 ml for environmental tritium. Diffusive and evaporative losses from rain gauges and storage containers are avoided by use of liquid paraffin or silicon oil. River samples were collected from the mid-stream sections or flowing portions on 10 daily basis for years 2004, 2006 and on daily basis for the year 2005. Standing water was avoided because the isotopic composition might have been affected by evaporation of standing water.

Snow and ice samples were collected from the Gangotri glacier. Few snow samples were collected in sealable plastic bags or containers. In order to avoid sublimation, re-crystallization, redistribution, melting and rainfall on snow, which alter the isotopic composition of snow and ice, the snow sampling was carried out shortly after every snowfall. Once, the snow was melted in containers, the water samples were transferred to plastic bottles. The collected samples were analysed by Stable Isotope Ratio Mass Spectrometer (SIRMS) at the Nuclear Hydrology Laboratory, Roorkee. Particularly, the Dual Inlet Isotope Ratio Mass Spectrometer was used for oxygen and hydrogen isotopes ratio analyses using the CO_2 equilibration method in order to determine $\delta^{18}O$ (Epstein and Mayeda, 1953) and Hokko beads were used for determining δD (Coleman *et al.*, 1982) using the standard procedure. The measurement precision for $\delta^{18}O$ was ± 0.1 ‰ and for δD was ±1‰. All the δD and $\delta^{18}O$ isotope data reported in this article correspond to VSMOW.

RESULTS AND DISCUSSION

Isotopic Composition of Rainfall

Isotopic values ($\delta^{18}O$) of rainfall measured for year 2004, 2005 and 2006 reveal significant variation in isotopic composition of precipitation during ablation period (April to October). The minimum depleted values of $\delta^{18}O$ of rainfall in the September months during the years 2004, 2005 and 2006 are –23.8‰, –30.3‰, and –23.2‰, respectively. The maximum enriched values of $\delta^{18}O$ in rainfall observed in the month of June 2004, 2005 and 2006 are –1.7‰, –3.6‰, and –4.7‰, respectively (Figure 2). The $\delta^{18}O$ and δD values show similar trend of variation during the study period. The different isotopic signature of rainfall falling during monsoon summer season reveals that source of moisture for precipitation in the months of July, August and September is different than the May and June. The depleted value of July August and September confirms that precipitation occur due to SW Monsoon vapour due to the continental and altitude effects while the source of moisture during summer months seems to be local evapotranspiration. The isotopic enrichment of premonsoon rain may also be due to the secondary evaporation of rain during fallout process.

Isotopic Composition of Stream Water

The spatial and temporal variations in the isotopic composition of river waters mainly depend upon the number and type of its sources. The variations in the observed δ_R, reflect the variable contributions from isotopically different sources, which can be evaluated if isotopic indices of the sources are known. However, the river water isotopic characterisation and its utility in studying hydrograph separation and river-aquifer interactions depend greatly on the spatial and temporal variations of isotopic ratios.

The δD and $\delta^{18}O$ variation in stream water reveals the systematic variation in $\delta^{18}O$ and δD values with time (Figure 3). The $\delta^{18}O$ values in initial river water (April to 20th June) ranged between –12‰ to –13‰. After the 20th June or in second phase $\delta^{18}O$ value of meltwater depletes slowly in July and August except few exception occurred during the precipitation in July and September when the stream $\delta^{18}O$ deplete abruptly. The isotopic values of initial stream water are very close to the $\delta^{18}O$ values of snow found between –9.7‰ to –14.4‰ (measured for few samples collected in May and June). This reveals that snow melt water is the main component in initial part of stream discharge (i.e., May and June). Due to melting of snow in initial phase, the glacier/ice gets exposed below the snow line and result into increased melting of ice/glacier. The meltwater generated due to melting of ice/glacier depleted the stream water isotopic composition after the 20th June. It indicates that ice/glacier is major component in second phase of stream discharge.

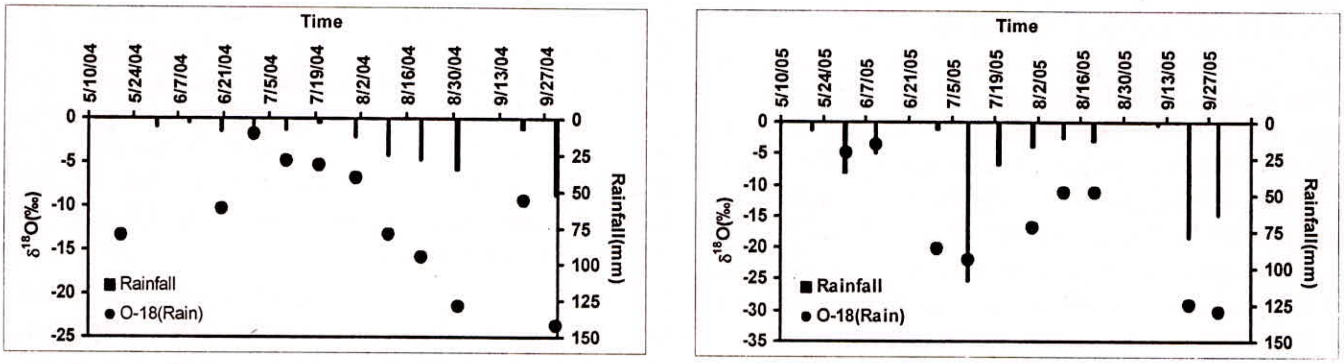

Fig. 2: Variation of $\delta^{18}O$ values in precipitation during ablation period in year 2004–2005

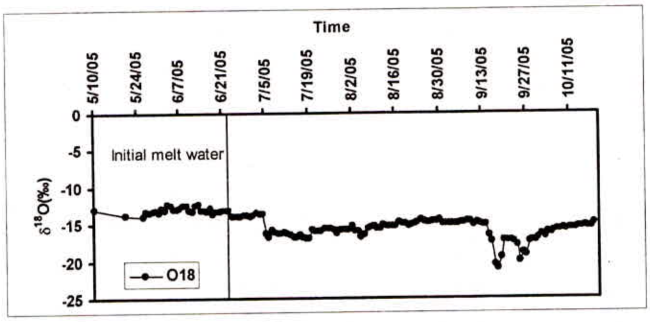

Fig. 3: Variation of $\delta^{18}O$ with time in stream water of Bhagirathi near snout

Discharge, Rain and Temperature Relationship

The recording of discharge of Bhagirathi river at gauging site reveals that the discharge in the river remain more or less in the order of is about 8.0 m^3/sec in May. The discharge is nearly constant upto June first week. As temperature starts increasing, discharge starts rising and the discharge become maximum in July/August (Figure 4). This shows strong correlation between temperature and discharge. The recession in discharge starts in September and then it quickly declines and reaches in order of discharge quickly declines and reaches to minimum level of 10.0 m^3/sec as it was recorded in initial period of May. The sharp decrease in temperature has also been recorded from the month of September. As heavy rainfall occurs in the months of July, August and September, stream discharge declines abruptly instead of increasing. The decreasing trend of river discharge in rainy period clearly shows that there is negative effect of rainfall on stream discharge (Figure 5). However, the abrupt change in isotopic composition of value stream water clearly shows that rain contribution as runoff joins the stream (Figure 6) while it is not reflected in hydrograph. Since, cloudy weather conditions during precipitation results to sudden decline in atmospheric temperature which reduce greatly melting of snow and ice. Thus, the discharge reduces even after runoff generated due to rainfall joins the stream discharge.

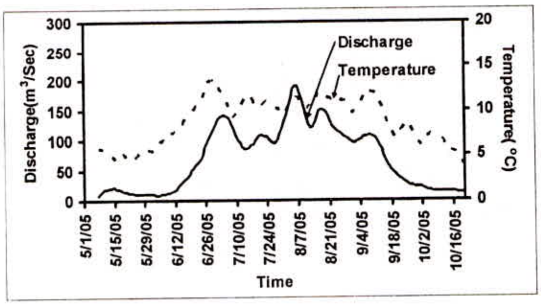

Fig. 4: Variations of discharge with temperature in Bhagirathi River at gauging site near snout

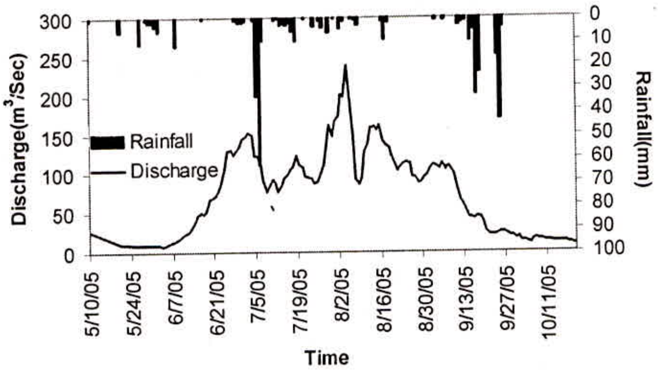

Fig. 5: Variation of stream discharge and its $\delta^{18}O$ composition with rainfall during ablation period in the year 2005

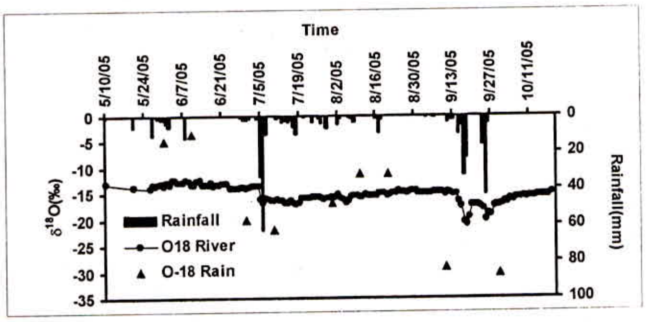

Fig. 6: $\delta^{18}O$ variations in melt water of Bhagirathi River, precipitation and rainfall amount with time near snout during ablation period in the year 2005

Hydrograph Separation

The hydrograph of Bhagirathi River at Gomukh site comprises of multiple peaks. The variation in discharge occurs due to variations in climatic conditions which affect the contribution of different components in stream discharge. To separate out the rainfall contribution in Bhagirathi river, stream water isotopic composition was studied. The $\delta^{18}O$ of stream water was found isotopically different during pre and post event of rainfall The sampling of the stream water pre and post rainfall event and rainfall was carried out in order to measure the changes in isotopic composition due to contribution of rainfall runoff The proportion of two components in total discharge can be separated out using two components model. The water mass balance equation can be written as,

$$Q_t = Q_{sm} + Q_r \qquad \dots (1)$$

Where, Q is discharge component, and subscripts t, sm and r represent total stream flow, snow/ice melt and runoff, respectively. Similarly, the isotopic mass balance equation can be written as,

$$\delta_t Q_t = \delta_{sm} Q_{sm} + \delta_r Q_r \qquad \dots (2)$$

Where $\delta = [(R_{sample} / R_{std}) - 1] * 10^3$ ‰

By substituting $Q_r = Q_t - Q_{sm}$ and rearranging equation (2), we get,

$$Q_{sm} = Q_t(\delta_t - \delta_r)/(\delta_{sm} - \delta_r) \quad \dots (3)$$

Using the equation (3), the runoff component can be separated out.

In order to separate out the runoff component, different event of precipitation were selected during the years 2004 and 2005. In the month of August 2004, large variation in isotopic composition of stream water was recorded at the time of rainfall. The $\delta^{18}O$ of rainfall occurred between 21st to 31st August 2004 was found –21.5‰, pre-storm stream water –15.5‰ and stream water during rainfall –17.9‰. The two components model reveals, the maximum runoff contribution in the order of 40% in stream discharge. Similarly, three rain events in year 2005 was monitored in the month of July and September 2005 (Figure 6). The maximum rainfall contribution to the tune of 40% was computed for the rainfall occurred in the month of July, upto 30% in case of rainfall occurred in September third week while up to 40% in case of rainfall occurred during September last week. The extent of change in isotopic composition of stream water is a function of proportion of rainfall contribution to the stream discharge at gauging site.

In order to estimate the total contribution of a rainfall event to the stream discharge, daily sampling was carried out and isotopic composition was measured. Hydrograph separation was carried out on daily basis for the month of July August and September in the year 2005, which revealed the rainfall contribution in order of 14% to 15% of the total stream discharge for each storm. Similarly, if the rainfall contribution of all the rain events occurred during ablation period of the year 2005 is considered, which comes out to be an aggregate of 3% of the total discharge of stream.

CONCLUSIONS

The variation in $\delta^{18}O$ of stream water with time reveals the varied contribution of snow, ice and rainfall in stream water due to variation in climatic conditions in an ablation period. Isotopic signature of stream water shows the snow dominates in stream discharge upto third week and ice/glacier melt dominates in the later period. The precipitation contribution is maximum up to 40% in stream discharge for a particular rain on a particular day. However, total contribution of rain event in stream discharge has been observed in the order of 14% to 15% only. But more precisely, the total contribution of all rainfall events during an ablation period is limited to only 3% of the total discharge of the stream.

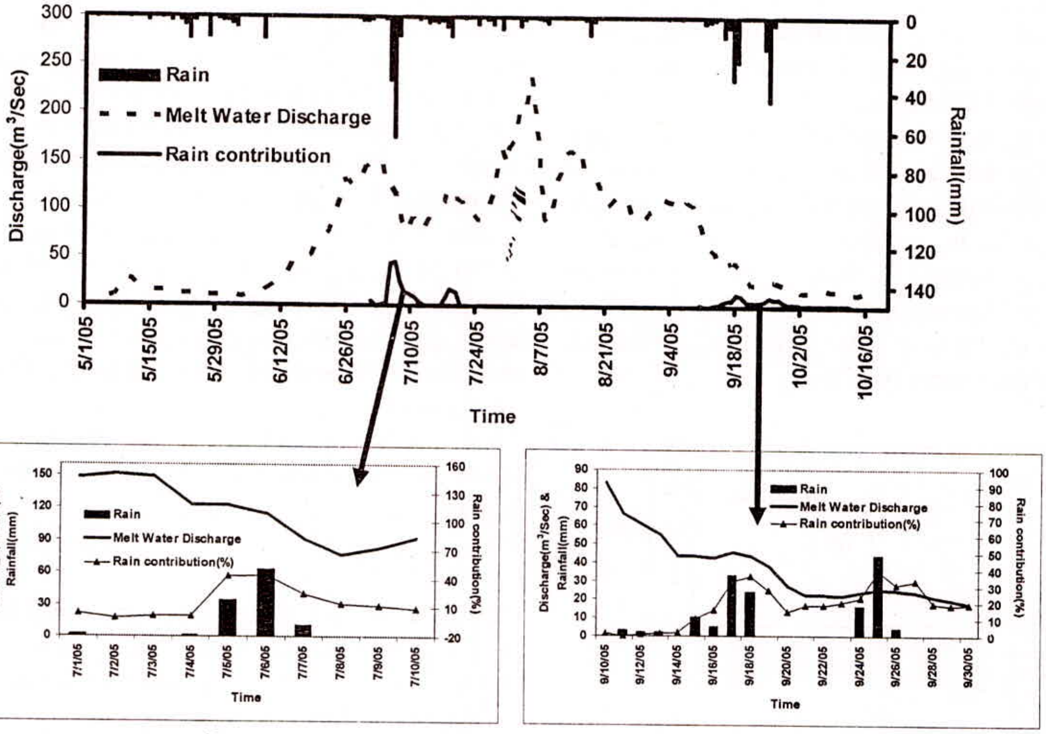

Fig. 7: Variation of $\delta^{18}O$ values in stream discharge due to rainfall of depleted $\delta^{18}O$ in year 2005

This study reveals that stable isotopes are very useful in separating the different component of stream discharge near snout while conventional have limitations. Further, isotopes can be used to study the melting pattern and magnitude of ice/glacier. The long term data of $\delta^{18}O$ of stream water near snout will be useful to study the impact of climate change on melting of Hamalayan glaciers.

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