

with 95.4% probability; Figure 2f). It will be appropriate to wait for the results of the analysis of botanical remains and artifactual evidences from the waterlogged area, to fine-tune the chronology of maritime features.

The excavation findings suggest that Pattanam had a key role in the early historic Indian Ocean trade. The archaeological evidence vouches for its cultural linkages with the Mediterranean, Red Sea, West Asia, Ganga Delta, Coromandal coast and Southeast Asian regions. The AMS dates confirm that the earliest settlement at Pattanam dates back to the Iron Age in the first half of the first millennium BC. The maritime features of the site according to the AMS dates are of the second half of the first millennium BC.

An interesting possibility emerging out of the present study could be the possibility of tracing back the antiquity of external contacts to the pre-Roman period. The presence of non-European, especially Nabatean (?) and West Asian variety of pottery could be another indication for maritime activities at Pattanam in the pre-Roman era.

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Estimation of contribution of southwest monsoon rain to Bhagirathi River near Gaumukh, western Himalayas, India, using oxygen-18 isotope

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Gaumukh is the snout of the Gangotri glacier located at an altitude of 4000 m in the Himalayas from where the snow and glacier-fed Bhagirathi River emerges. Snow, ice, river discharge and rainfall samples were collected for stable isotope ($\delta^{18}\text{O}$) analysis along with other hydrometeorological data during the ablation period (May to October) in 2004 and 2005 at Bhojwasa, 3 km downstream of Gaumukh. The variation in river isotopic composition ($\delta^{18}\text{O}$) with time shows the varied percentage of snow, glacier and rain contribution in the flow of the Bhagirathi River during the ablation period. The discharge of the Bhagirathi River shows positive correlation with temperature and negative correlation with the rain event. The enriched $\delta^{18}\text{O}$ values of river flow (–12 to –13.0‰) from May to June and its depletion afterwards reveal that snowmelt dominates the river discharge during May and June while ice/glacier melt dominates in the subsequent months of the ablation period. The contribution of rain was found maximum up to 40% of the total discharge of the river on the day of the rainfall. The complete hydrograph separated out for three rain events occurred in July and September 2005, revealed the rain contribution to the tune of 14–15% of the total river discharge. The contribution of the total rainfall which occurred during the ablation period was estimated to be only 3% of the total discharge. The results show that the melting rate of snow and glacier decreases due to decrease in temperature during the rainy period. This fact clearly explains the phenomenon of decrease in overall discharge of snow and glacier-fed rivers during the rainfall period at higher altitudes or near the snout.

Keywords: Glacier, ice, monsoon, snow, stable isotopes.

THE snow and glacier melt run-off contributes significantly to all North Indian Himalayan rivers during summer, when demand for water increases for hydropower, drinking, irrigation, etc. Due to lack of information on hydrological processes of snow/glacier regime and assured availability of melt water, water resources management policies at the lower reaches of the glacier-fed rivers are

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often formulated without considering the impact of snow and glacier on river hydrology¹. Depending upon the prevailing climatic conditions, the melt water contribution from the glaciers to Himalayan rivers starts in May, after depletion of accumulated seasonal snow due to rise in atmospheric temperature. Usually the melt contribution from the glaciers starts during summer months after the melting of seasonal snow and continues till October². Precipitation in the form of snow occurs only during October–March, when the primary source of moisture is related to the winter monsoon and western disturbances. During maximum snow accumulation period, the snow-line comes down to about 1500 m in the western Himalayas and to about 3000 m in the eastern Himalayas. The southwest monsoon also plays an important role during the ablation period of the Himalayan glaciers³. Generally, the contribution of snow and glacier melt run-off to annual flow of the different Himalayan rivers has been studied on meso-scale covering large areas, considering the glaciers and seasonal snow cover area as a single unit^{4,5}. For a few glaciers of the Himalayan region, run-off and sediment load transportation studies have been carried out by various workers^{6–10}. Therefore, it becomes essential to understand the contribution of snow and glacier melt to the river in the headwater region along with the impact of rain on river discharge. But it is difficult to segregate the different components of river discharge using conventional techniques due to lack of required data from this inaccessible terrain.

Few studies in the Ganga, Brahmaputra and Indus basins have been conducted based on stable and radioisotopes to understand the hydrological process in the Himalayan region. Ramesh and Sarin¹¹ observed that the δD and $\delta^{18}O$ values of these rivers fall on the Global Meteoric Water Line (GMWL) and estimated the altitude effect in δD and $\delta^{18}O$ using river isotopic data. Bartarya *et al.*¹² proposed an equation with a slope of ~ 7.1 and intercept of ~ 15 for the Gaula basin of the Kumaun Himalayas based on randomly selected individual storm events. Pande *et al.*¹³ based on $\delta^{18}O$ – δD and d -excess of the headwaters of the Indus and its tributaries, inferred the source of precipitation and altitude effect. Dalai *et al.*¹⁴ studied the isotopic composition of Yamuna River and its relationship with water chemistry. Nizampurkar *et al.*³ studied the climatic changes and ice dynamics of Dokriani Glacier by dating the ice and measuring the isotopic composition of snow and ice. Studies based on $\delta^{18}O$ in snow/ice and ice core from the Tibetan (Xizang) Himalayas have addressed the seasonal relationship between $\delta^{18}O$ in snow/ice and air temperature and moisture sources^{15–17}. The status of the studies shows that the contribution of snow, ice and rain in the river discharge in the headwater region has not been investigated. In the present study, the stable isotope data generated for 2004 and 2005 are used to understand the contribution of snow and glacier melt in the Bhagirathi River. This study is an attempt to estimate

the contributions of different water sources, namely rain, snow and glacier are being estimated using isotopic techniques in the Bhagirathi River near Gaumukh, the origin of the Ganges.

The Gangotri glacier is the largest glacier in western Himalayas. The study area falls in Uttarkashi District, Uttarakhand, between latitudes $30^{\circ}43'N$ and $31^{\circ}01'N$, and between longitudes $79^{\circ}0'E$ and $79^{\circ}17'E$ (Figure 1). The proglacial meltwater river, 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 Gaumukh (the mouth of a cow). Gaumukh is considered as the origin of the Ganga River. The main Gangotri glacier (length, 30.20 km; width, 0.2–2.35 km; area, 86.32 km²) forms the trunk part of the Gangotri glacier system. The major glacier tributaries of the Gangotri glacier system are the Raktvarn glacier (area, 55.30 km²), Chaturangi glacier (area, 67.70 km²), Kirti glacier (area, 33.14 km²), Swachand glacier (area, 16.71 km²), Ghanohim glacier (area, 12.97 km²), Meru glacier (area, 6.11 km²), Maindi glacier (area, 4.76 km²) and a few others having a glacierized area of about 3.08 km² in total. The total catchment area up to the sampling location is about 556 km². Out of this, a total area of 286 km² is glacierized². The elevation range of the Gangotri glacier varies from 4000 to 7000 m, and the elevation of the study area up to the gauging site lies between 3800 and 7000 m.

In order to measure the discharge of the river and weather parameters, a hydrometeorological observatory was established near Bhojwasa by the National Institute of Hydrology (NIH), Roorkee. To monitor the water-level

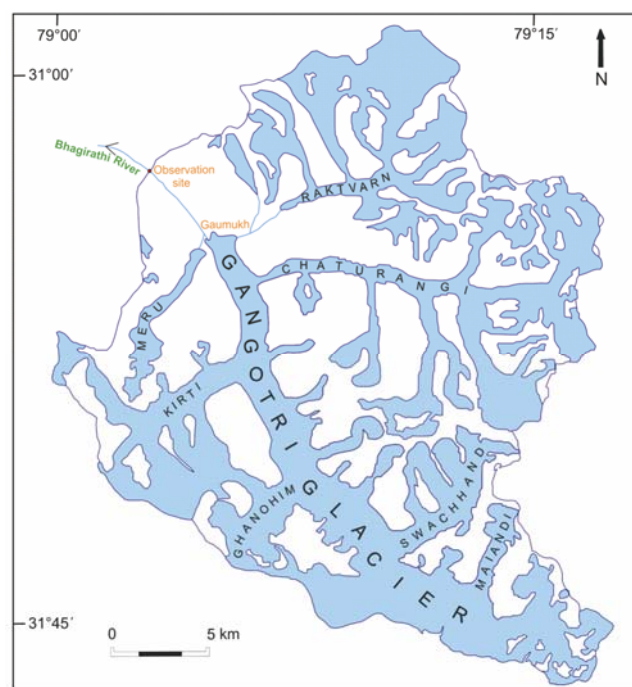


Figure 1. Location map of the study area.

data, an automatic water-level recorder was installed in a stilling well constructed near the right bank of river. To measure the $\delta^{18}\text{O}$ value of rainfall, integrated monthly and ten daily samples were collected during the ablation period of 2004 and 2005, using an ordinary raingauge. From the integrated samples, 20 ml water sample was collected for stable isotopic analysis ($\delta^{18}\text{O}$) measurements. Diffusive and evaporative losses from raingauges were avoided by collecting the water daily in a double-lid plastic container, while evaporation from storage containers was avoided by sealing the outer cap with paraffin. Discharge samples were collected from the flowing portions on a ten daily basis for 2004 and on a daily basis for 2005. Water sampling from standing water was avoided because the isotopic composition is 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, snow sampling was carried out just after every local snowfall. Once the snow melted in the 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, NIH, Roorkee. Particularly, the Dual Inlet Isotope Ratio Mass Spectrometer was used for measuring oxygen and hydrogen isotope ratios. The CO_2 equilibration method was used to determine $\delta^{18}\text{O}$, while the H_2 equilibration method with Hokko beads was used to determine δD following standard procedure^{18,19}. The measurement precision for $\delta^{18}\text{O}$ was $\pm 0.1\text{‰}$ and for δD it was $\pm 1\text{‰}$. All the $\delta^{18}\text{O}$ isotope data reported in this study correspond to VSMOW.

The recording of discharge of the Bhagirathi River at the gauging site reveals that it remains more or less in the range $8.0\text{--}10\text{ m}^3/\text{s}$ during May/first week of June (Figure 2). As the temperature increases, the discharge increases; higher discharge ($100\text{--}180\text{ m}^3/\text{s}$) has been recorded in July/August when the temperature reaches a maximum of $10\text{--}12^\circ\text{C}$ (Figure 2). Thus features of discharge and

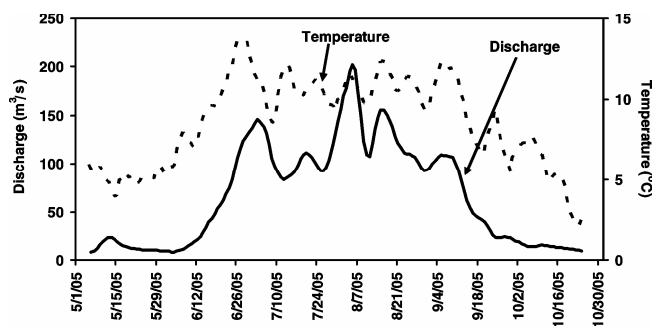


Figure 2. Variations of moving average of discharge with temperature in the Bhagirathi River at the gauging site near the snout.

temperature show strong correlation between air temperature and discharge of the Bhagirathi River. The recession of discharge starts in September and quickly reaches the level of $10.0\text{ m}^3/\text{s}$, as is observed in the initial part of May. A sharp decrease in air temperature has also been recorded during July–September when heavy rain events occur (Figures 2 and 3). It has been observed that during the sharp decline of air temperature due to cloudy weather condition, the river discharge also declines abruptly instead of increasing (Figure 3). The decreasing trend of river discharge with rain events apparently indicates no effect of rainfall on river discharge. Therefore, it becomes difficult to estimate the impact of rain on discharge in the case of snow and glacier-fed rivers at higher altitudes using the conventional techniques. It also posed a problem in estimating the contribution of rain to the discharge of the Bhagirathi River. Consequently, isotopic signatures of river and rainfall were employed to solve this problem. The abrupt change in isotopic composition of the river after the rain events is only due to run-off generated by contemporaneous rain joining the river (Figure 4). However, the decrease in river discharge has resulted due to cloudy weather conditions during rainfall and a sudden decline of atmospheric temperature. The decline in atmospheric temperature reduces the melting of snow and ice. Thus the overall discharge of the river has declined which includes the run-off contributed by rain and snow and glacier.

Isotopic values of rainfall ($\delta^{18}\text{O}$) measured for 2004 and 2005 reveal significant variation in isotopic composition of precipitation during the ablation period. The maximum depleted rainfall in terms of oxygen isotope ($\delta^{18}\text{O}$) observed in September during 2004 and 2005 was -23.8 and -30.3‰ respectively. Similarly, the maximum enriched $\delta^{18}\text{O}$ in rainfall observed during June 2004 and 2005 were -1.7 and -3.6‰ respectively (Figure 5). However, it was noticed that rainfall bears enriched values of $\delta^{18}\text{O}$ during May and June compared to $\delta^{18}\text{O}$ values during July–September. The different isotopic signatures of rain during premonsoon (May and June) and monsoon season (July–September) reveal that the source of moisture for precipitation during May and June is different from that during July–September. The depleted isotopic signature

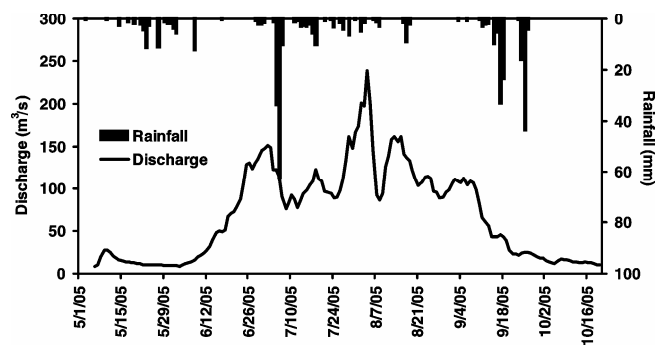


Figure 3. Variation of river discharge with rainfall in the ablation period during 2005.

of rain during July–September becomes a unique feature and is important for various hydrological studies. The depleted $\delta^{18}\text{O}$ values of rain during July–September confirm that precipitation during these month occurs due to the SW monsoon vapours which deplete due to the continental and altitude effects, while the source of the moisture during summer months may be dominated by local evapotranspiration. The isotopic enrichment of premonsoon rains (May and June) may also be due to secondary evaporation of rain drops during the fallout process.

The isotopic signatures of fresh snow and surface ice samples collected from different altitudes in the accumulation and ablation zones of the western Himalayan glaciers by various workers and under the present study from the Gaumukh snout are presented in Tables 1 and 2.

The results clearly indicate that fresh snow bears more enriched isotopic signature than the glacier. This is possible as the glacier is formed from snow that occurs at higher

altitude and it also takes several decades for transformation from snow to ice. Based on ^{32}Si and ^{210}Pb radioactivity, the ages of Nehnar, Chhota Shigri and Dokriani glaciers were calculated to be about 500, 250 and 400 years respectively⁴. The depleted $\delta^{18}\text{O}$ of these dated glacier snouts revealed that these regions had a cooler atmosphere (by a few degrees) during their formations.

The spatial and temporal variations in the isotopic composition of the river mainly depend upon the number and type of its sources. Variations in the observed $\delta^{18}\text{O}$ reflect the variable contributions from isotopically different sources, which can be evaluated if isotopic indices of the sources are known. However, the river isotopic characterization and its utility in studying hydrograph separation and river–aquifer interactions depend greatly on the spatial and temporal variations of isotopic ratios.

The $\delta^{18}\text{O}$ values of river water during pre-monsoon (April to June) were found to be between -12 and -13‰ . The $\delta^{18}\text{O}$ values further deplete slowly during July with an abrupt depletion in the order of -17‰ in the first week of July (Figure 4). The depleted $\delta^{18}\text{O}$ signatures continue in the remaining months of August and September, with slight enrichment and abrupt depletion. The abrupt depletion of $\delta^{18}\text{O}$ in July and September is triggered by a heavy rainfall event. It has been observed that the isotopic values of the river initially follow the $\delta^{18}\text{O}$ values of snow as shown in Table 1 (-4.0 to -14.4‰ for samples collected during May and June). This suggests that snowmelt dominates in the river discharge at the initial stage (during May and June). Due to melting of snow in the initial phase, the glacier/ice gets exposed below the snow line and results into melting of ice subsequently along with snow melt at higher altitude. The melt water generated due to melting of glacier bears depleted isotopic signatures. Hence the depletion in isotopic composition of the river starts from the last week of June/first week of July. It clearly indicates that glacier melt run-off dominates river discharge during July and August.

The hydrograph of Bhagirathi River at Gaumukh comprises of multiple peaks. The variation in discharge occurs due to variations in climatic conditions which affect the contribution of different components to river discharge. To separate out the rainfall contribution in the Bhagirathi River, the isotopic composition of river water and observed rainfall was studied. The $\delta^{18}\text{O}$ value of the river was found to be isotopically different during pre- and post-event of rainfall. The pre-event river $\delta^{18}\text{O}$ represents a combined signature of snow and glacier melt, while the post-event river represents mixed signatures of rain, snow and glacier components. The significant variation in $\delta^{18}\text{O}$ value of the river due to the SW monsoon rains observed was during July and September 2005 (Figure 4). The isotopic composition of pre-event river (-14 to -16‰) was found sharply depleted to -20‰ , due to much depleted rain of -30.3‰ . The proportion of the two components in total discharge can be separated out using

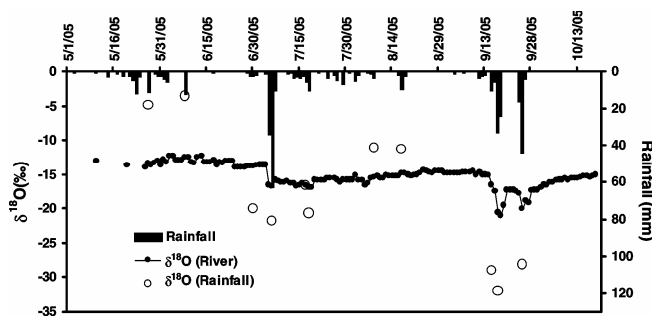


Figure 4. Variation of $\delta^{18}\text{O}$ in the Bhagirathi River and rainfall with time at the gauging site during the ablation period in 2005.

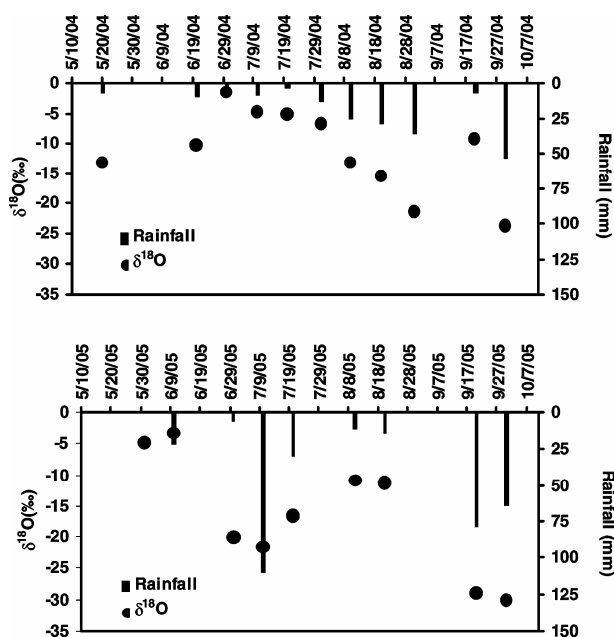


Figure 5. Variation of $\delta^{18}\text{O}$ in precipitation during the ablation period in 2004–05.

Table 1. $\delta^{18}\text{O}$ values of snow measured under different studies

Location	Altitude (m)	$\delta^{18}\text{O}$ (‰)	Investigators
Chhota Shigari and Dokriani	4050–4750	–5 to –9	Nijampurkar <i>et al.</i> ³ Nijampurkar and Rao ²⁰
	4695	–4.5 to –7.2	
	4695	–5.0 to –23.0	
Gaumukh, near Bhojwasa	3800	–11.6	Present study
	3800	–13.9	
	3800	–9.7	
	3800	–10.1	
	3800	–11.7	
	3800	–4.0	
	3800	–14.0	

Table 2. $\delta^{18}\text{O}$ values of ice/glacier reported by various investigators

Location	Altitude (m)	$\delta^{18}\text{O}$ (‰)	Investigators
Rohtang	3748	–18.1	Pande <i>et al.</i> ¹³
Balacha La	4650	–15.9	
Thanglang La	5210	–24.7	Nijampurkar <i>et al.</i> ³ Nijampurkar and Rao ²⁰
Zozilla	3540	–12.2	
Khardung La	5629	–17.2	
Khardung La	5649	–15.3	
Dokriani	4836	–11 to –15.2	
Chhota Shigri	4100–4600	–6 to –11	Present study
Changme Khangfu		–12 to –17	
Gaumukh	4000	–18.5	Present study
	4000	–13.37	
	4000	–18.1	
	4000	–14.5	
	4000	–13.5	
	4000	–15.0	
	4000	–14.4	

a two-component model. The water mass balance equation can be written as:

$$Q_t = Q_{sm} + Q_r, \tag{1}$$

where Q is the discharge component and t, sm and r represent total river flow, snow/ice melt and rain contribution respectively. Similarly, the isotopic mass balance equation can be written as:

$$\delta_t Q_t = \delta_{sm} Q_{sm} + \delta_r Q_r, \tag{2}$$

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

By substituting $Q_r = Q_t - Q_{sm}$ and rearranging eq. (2), one gets

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

Using eq. (3), the run-off component can be separated out.

In order to separate out the rainfall generated run-off component, different events of precipitation were selected during 2004 and 2005. During August 2004, large variation in the isotopic composition of the river was recorded at the time of rainfall. The $\delta^{18}\text{O}$ value of rainfall that occurred between 21 and 31 August 2004 was found

to be –21.5‰, pre-storm river, –15.5‰ and the river during rainfall, –17.9‰ (Figure 4). The two-component model shows the maximum run-off contribution in the order of 40% in the river discharge. Similarly, three rain events were monitored during July and September 2005 (Figure 6). Maximum rainfall contribution to the tune of 40% was computed for rainfall that occurred during July; up to 30% in case of rainfall that occurred in the third week of September, and up to 40% in the case of rainfall that occurred during the last week of September. The extent of change in isotopic composition of the river was found to be a function of the proportion of rainfall contribution to the river discharge at the gauging site during rainfall above 20 mm (Figure 4).

In order to estimate the total contribution of a rainfall event to the river discharge, daily sampling was carried out and isotopic composition was measured. Hydrograph separation was carried out on daily basis for July–September in 2005, which revealed rain contribution in the order of 14–15% of the total river discharge for each storm (Figure 6). Similarly, rainfall contribution of all the rain events that occurred during the ablation period of 2005 was computed, which was an aggregate of 3% of the total discharge of the river.

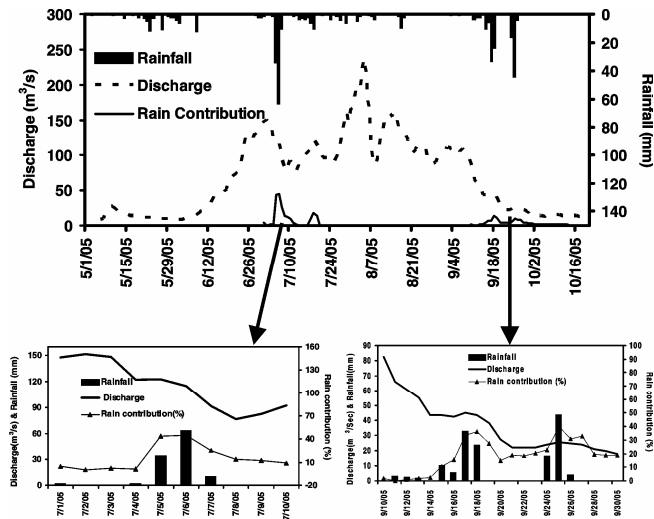


Figure 6. Rainfall contribution in the Bhagirathi River using two-component model for different rain events that occurred during the ablation period in 2005.

The variation in $\delta^{18}\text{O}$ of river discharge with time clearly indicates the varied contribution of snow, ice and rain in the river due to variation in weather conditions in an ablation period. Isotopic signature of river shows that snow dominates in the river discharge up to June and glacier melt dominates in the later period. The maximum contribution of rainfall in the river discharge was estimated up to 40% during the day of rainfall. While the contribution of each rain event was found to be in the range 14–15% of the river discharge. But the total contribution of all rain events during an ablation period was limited to only 3% of the total discharge of the Bhagirathi River at gauging site. The isotopic signatures of rain and river (pre- and post-event of rainfall) revealed that the decrease in discharge of the Bhagirathi River near the snout during rainfall is due to considerable decrease in snow and glacier melt run-off which is caused due to decrease in atmospheric temperature during rainfall.

The depleted $\delta^{18}\text{O}$ signature of rain during July–September becomes unique and important for various hydrological studies. The present study reveals that stable isotopes are useful in segregating the different components of river discharge near the snout, while conventional techniques have limitations. The long-term data of $\delta^{18}\text{O}$ value of the river near the snout would be useful to study the impact of climate change on melting of the Himalayan glaciers.

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