


Towards the understanding of the flash flood through isotope approach in Kedarnath valley in June 2013, Central Himalaya, India

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Abstract During middle June 2013, Kedarnath valley in Rudraprayag district of Uttarakhand, India, was affected by catastrophic rainfall episode that caused massive loss of human lives and damage to the properties and livestock. Isotopic signatures of rainfall, snow/ice melt water and river water of Mandakani River were measured from 25 May 2013 to 16 June 2013, and these isotopic signatures are used to estimate the contribution of rainfall-derived runoff on flooding day. The result indicates that during the course of flood in Mandakani River, isotopic signature of river water was -15.97% , whereas average isotopic signature of river before the flood shows -10.39% . By using the two-component mixed model, the contribution of rainfall-derived runoff is found to be 78% and the contribution of snow/ice melt runoff is 22% during the flash flood in Mandakani River surrounding the Shri Kedarnath Temple, Central Himalaya, India.

Keywords Kedarnath valley · Flash flood · Isotope · Snow/glacier melt · Rainfall-derived runoff

1 Introduction

Three major hazards are associated with the Himalayan region, i.e. earthquakes, flash floods and land slides. Monsoonal precipitation and snowmelt are the major predictable source for periodic flooding in rivers throughout the world, while intense localized

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rainfall can result in unexpected flash flood during any season (Costa 1987). In India, heavy rainfall events and flash floods are not new phenomena. However, the catastrophic flash floods like the one on 16–17 June 2013 in Kedarnath area were not witnessed in recent history. Kedarnath valley, besides being most sacred pilgrimage centre, is also famous for tourist attractions particularly during the summer months. For this reason, the flux of population to the area is large in summer, particularly at the time of this event. This catastrophic flash flood took few minutes to gulp thousands of lives and obliterated huge property. It was India's worst natural disaster since 2004 Indian Ocean tsunami. Numerous reports have been published on Kedarnath flash flood (Dobhal et al. 2013; Uniyal 2013; Asthana and Asthana 2014). In the past 2–3 decades, frequency and magnitude of occurrence of flash floods in the Himalayan rivers have increased due to climate change (IPCC 2013). In this study, an attempt has been made to analyse isotopic signature of the flood water event to understand the major contributing factor in this catastrophic flood.

Isotope hydrograph separation (IHS) is being used to estimate the contribution of different components (snow vs. rainfall) to the river water since the pioneering work of Craig (1961). Studies carried out during the last few decades have established that stable oxygen and hydrogen isotope ratios provide useful tools for river flow studies (Dincer and Payne 1971; Mrartinec et al. 1974; Hooper and Shoemaker 1986; Obradovic and Sklash 1986; Maule and Stein 1990; Rai et al. 2009). These stable isotopes ($\delta^{18}\text{O}$, δD) in the river flow of Himalayan rivers, namely the Ganga, Yamuna and Indus rivers, have been used successfully to study the characteristics of the rivers (Ramesh and Sarin 1992; Dalai et al. 2002; Jain et al. 2011; Ahluwalia et al. 2013). Maurya et al. (2011) and Ahluwalia et al. (2015) have estimated the contribution of different components, i.e. snow/ice melt water, base flow and rain water in Ganga and Beas rivers. Unlike applied tracers, stable isotopes are added naturally at the watershed scale by rain and snowmelt events. These environmental isotopes (applied through meteoric processes) can be used to trace and identify different air and water masses contributing precipitation to a watershed as the stable isotope composition of water changes only through mixing and well-known fractionation processes that occur during evaporation and condensation.

2 Study area

This study focuses on the Shri Kedarnath Temple area which is located in the Rudraprayag district of Uttarakhand state in the flood plain of the Mandakani River (tributary of Alaknanda River) of Garhwal Himalaya. Mandakani River emerges from Chorabari Glacier ($30^{\circ}46'20.58''\text{N}$; $79^{\circ}2'59.381''\text{E}$), which is a medium-sized compound valley-type glacier covering an area of $\sim 6.6 \text{ km}^2$. The glacier is located in the Mandakani River basin of the Alaknanda catchment (a tributary of the River Ganga) (Fig. 1). The head of the glacier lies at an elevation of 6500 m asl, whereas the snout is located at 3865 m asl. This glacier is the source of the Mandakani River which eventually joins the Alaknanda River near Rudraprayag.

3 Storm of June 2013

Heavy rainfall was reported during the middle June 2013 in the whole Central Himalaya (Fig. 2). High-intensity flash flood was reported surrounding the region of important pilgrimage centres, namely Gangotri, Yamunotri, Kedarnath, Badrinath and Hemkund Sahib

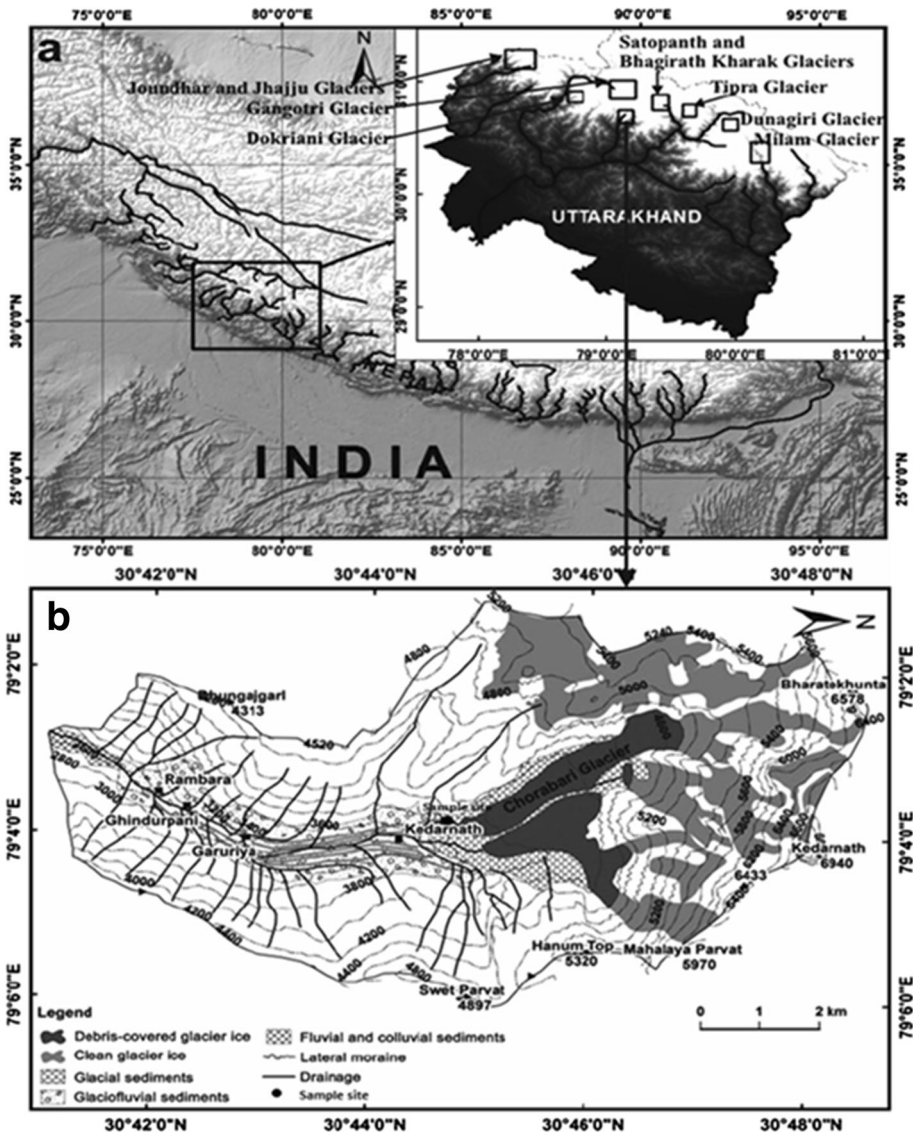


Fig. 1 Study area of Kedarnath valley, Central Himalaya, India (Dobhal et al. 2013)

of Higher Himalaya. Among these areas, Kedarnath region was one of the worst affected areas during this period. This area belongs to remote valley with no vehicular access. This place generally remains rushed in summer period with high volume of pilgrimage who come here to pay their reverence and devotion to the historic temple of Lord Shiva at Kedarnath. Wadia Institute of Himalayan Geology (WIHG) observatory at Chorabari Glacier base camp (3820 m asl) near Shri Kedarnath Temple recorded 325 mm rainfall in 24 h from 15 June (5:00 p.m.) to 16 June (5:00 p.m.) 2013. This heavy rainfall caused flash flood in this valley.

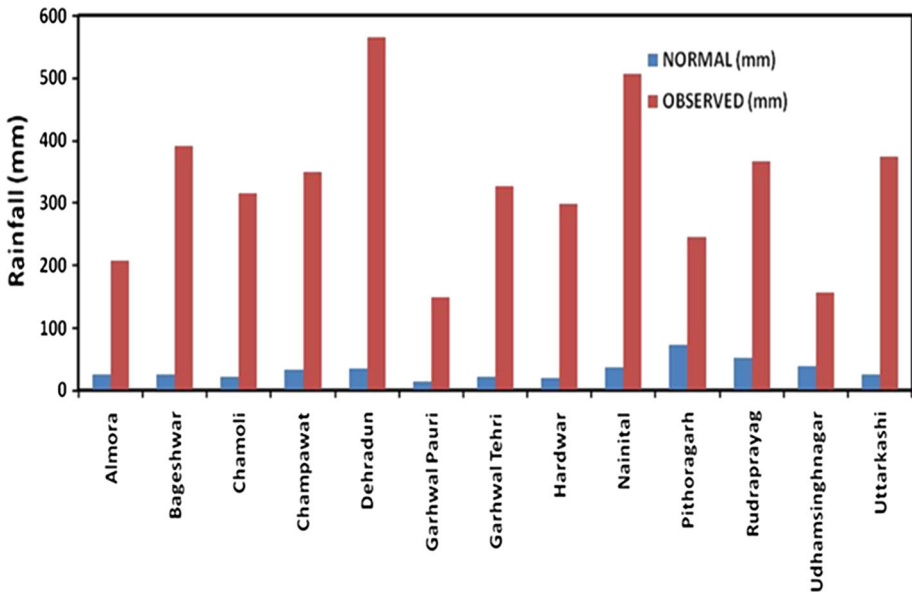


Fig. 2 Monthly rainfall in June 2013 of Uttarakhand district, India (Source: IMD 2013)

The flash flood brought lots of debris in the form of medium to very large boulders (10–15 m) to the downstream indicating high intensity and load-carrying capacity of this flash flood in the Kedarnath valley (Fig. 3). This flash flood event struck the entire Kedarnath valley leaving the trail of devastation. Shri Kedarnath Temple is one of the few structures in this region which escaped with relatively minor damage.

4 Database preparation

4.1 Sampling and analysis

A field work was carried out before the flood from 21 May 2013 to 2 June 2014 to monitor and undertake the isotopic study for snow/ice melt runoff. In order to analyse the isotopic signatures of the Mandakani River, a sampling site was set up above the Shri Kedarnath Temple and collection of samples of river water, snow/ice melt water and rainfall started from 24 May 2013 (Fig. 1). Field work was completed on 2 June 2013, and sample collection was continued by the watch and wards till 16 June 2013. However, they managed to escape themselves with such a terrible situation on 17 June 2013 morning from the base camp (near snout).

Few samples including 16 June sample of rain and river flow were in good condition with appropriate labels which were brought for analysis by the field team when some communication was established in the valley after flash flood. We analysed these samples for $\delta^{18}\text{O}$ and δD using stable isotope mass spectrometer (IRMS). A dual-inlet isotope ratio mass spectrometer was used for measuring oxygen ($\delta^{18}\text{O}$) and hydrogen (δD) isotope ratios. The CO_2 equilibration method was used to determine $\delta^{18}\text{O}$, while the δD equilibration method with hokobeads was used to determine δD following the standard



Fig. 3 Photographs showing the impact of flash flood surrounding the Shri Kedarnath Temple

procedure. For stable isotope measurements, samples were collected in pre-cleaned 20-mL polypropylene bottles (Tarsons). The bottles were rinsed thoroughly with sample water at the study site, filled with water samples, tightly capped (to prevent evaporation and exchange with atmospheric moisture) and transferred to the laboratory for isotopic analyses.

For oxygen ($\delta^{18}\text{O}$) and hydrogen (δD) isotopes, 400 μL water samples were taken and hokobeads were used as the catalyst. Along with each batch of samples, secondary standards developed with reference to primary standards (i.e. V-SMOW, SLAP, GISP) were also measured and the final values were calculated using a triple-point calibration equation. The overall precision, based on ten points of repeated measurements of each sample, was within $\pm 0.1\%$ for $\delta^{18}\text{O}$ and $\pm 1\%$ for δD .

5 Methodology

5.1 Isotopic approach

In isotopic approach, two- and three-component models are usually applied to separate out the river flow component. In the present study, a two-component mixed model was applied for the pre-event (flash flood) and synevent in the Kedarnath valley as river flow was contributed only with two components, i.e. rainfall-derived runoff and snow/glacier melt runoff. In order to measure the changes in the isotopic composition of the river flow, sampling of the river flow, snow/glacier melt water and rainfall water was carried out. The water balance equation can be written as

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

where Q is the discharge component and subscripts “t”, “sm” and “r” represent total river flow, snow/ice melt runoff and rainfall runoff, respectively. Similarly, the isotopic balance equation can be written as

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

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

From Eqs. (1) and (2), we get

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

Using Eq. (3), the snow/ice melt water and rainfall-derived runoff component can be separated out.

6 Results and discussion

6.1 Temporal variation of $\delta^{18}\text{O}$ in melt water and rain

The temporal variation in the isotopic composition of the river water mainly depends on the number and type of the sources of water. Variations in the observed $\delta^{18}\text{O}$ reflect the variable contribution from isotopically different sources, which can be evaluated if isotopic indices of the sources are known.

In this study, an attempt was made to find out the isotopic indices as well as the contribution of the different components to the Mandakani River during the flash flood. Availability of the samples and hydrometeorological data were the major constraints as the automatic weather station (AWS) installed at base camp was completely vanished and washed away during the flash flood. The approximate amount of the rainfall on the day of flash flood was verbally communicated to us by the watch and ward staff. We brought out the river samples from 24 May to 31 May 2013 along with us after completion of field work on 2 June 2013. Snow and ice samples were also collected from 24 May to 2 June 2013 during the field work, and these were also brought out with us. Sampling of the rain water and river water at base camp was carried out continuously on daily basis by the watch and ward. However, only few samples of rain-derived runoff and river water for June months were available (Table 1), but isotopic signature of these samples leads us to estimate the contributing factor for the flood. The $\delta^{18}\text{O}$ and δD of river and rainfall-derived runoff measured near snout Chorabari Glacier (Above Kedarnath temple) are also given in Table 1.

The results show that fresh snow bears more enriched isotope signature than the ice. This is possible as the ice is formed from snow that occurs at higher altitude and it also takes several decades to transform into ice. The $\delta^{18}\text{O}$ signature of river water during pre-flood (24 May to 31 May) was found between -10.73 and -10.07 ‰ , whereas δD signature were found between -68.51 and -62.80 ‰ (Fig. 4). It is observed that depletion in isotopic signature takes place from June onwards and it continues till September (Fig. 4). The $\delta^{18}\text{O}$ signature of river ranged from -11.73 to -10.40 ‰ in June except for flash flood day, which was -15.97 ‰ (Table 1). The isotopic signature of snow varies from -10.81 ‰ to -7.49 ‰ in the Kedarnath valley, whereas isotopic signatures of ice were observed with the range from -17.07 to -12.15 ‰ . It is observed that the isotopic

Table 1 Isotopic composition of river and rainfall at Chorabari Glacier base camp sampling site

Date	River			Rain			
	$\delta^{18}\text{O}$	δD	d-excess	$\delta^{18}\text{O}$	δD	d-excess	
24-May-13	-10.39	-62.8	20				
25-May-13	-10.51	-64.31	20				
26-May-13	-10.44	-63.7	20				
27-May-13	-10.29	-65.51	17				
28-May-13	-10.07	-66.04	15				
29-May-13	-10.73	-68.51	17				
30-May-13	-10.39	-68.01	15				
31-May-13	-10.3	-66.46	16				
01-Jun-13	-10.4	-66.71	16				
03-Jun-13	-11.29	-68.24	22				
04-Jun-13	-11.39	-69.36	22				
06-Jun-13	-10.99	-68.02	20	-5.73	-27.79	18	
11-Jun-13	-11.73	-71.98	22	-6.53	-34.47	18	
12-Jun-13	-11.54	-72.46	20				
13-Jun-13				-10.55	-66.93	17	
15-Jun-13	-11.41	-72.12	19				
16-Jun-13	-15.97	-112.06	16	-17.77	-129.79	12	
		Snow			Ice		
		$\delta^{18}\text{O}$	δD	d-excess	$\delta^{18}\text{O}$	δD	d-excess
Samples of snow ice collected during field work near snout (3800–4200 amsl)		-7.48	-39.27	20	-14.71	-104.79	12
		-10.75	-66.70	19	-12.61	-92.16	8
		-10.81	-73.89	12	-12.50	-89.26	10

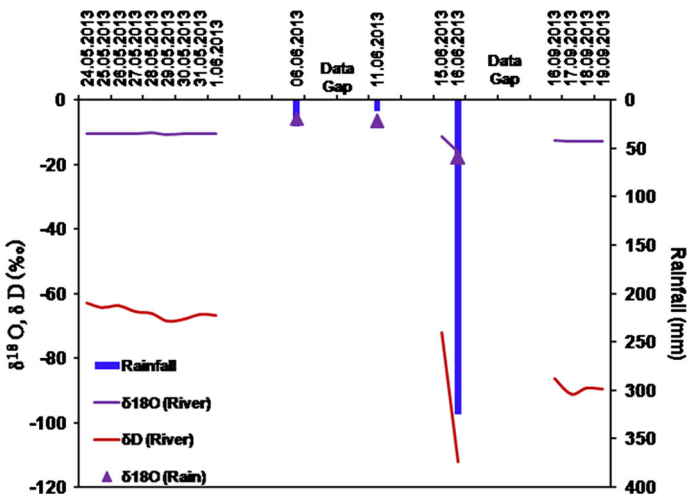


Fig. 4 Isotopic signature of Mandakani River, special focus on 16 June 2013, Central Himalaya, India

signature of river initially follows the $\delta^{18}\text{O}$ signature of snow (Fig. 5). This suggests that snowmelt dominates in the river discharge in the initial stage, i.e. starting of summer season. Due to melting of snow in the initial phase, the ice exposed below the snowline and results into melting of ice subsequently along with snowmelt at higher altitude. Satellite images of 28 May and 21 June 2013 also report the fresh snowfall, and about 30 % more snow cover during this time the Mandakani catchment area (Fig. 6) (NRSC report). However, this is very abnormal phenomena to have such large quantity of snowfall during June in the headwater region of Mandakani River.

The estimation of different components in the river discharge depends on their isotopic signatures. With the importance of the Kedarnath flash flood event, we tried to understand the flash flood responsible factors using limited isotopic data sets. To avoid the uncertainty between snow and ice, river water isotopic signature of non-rainy day was considered as

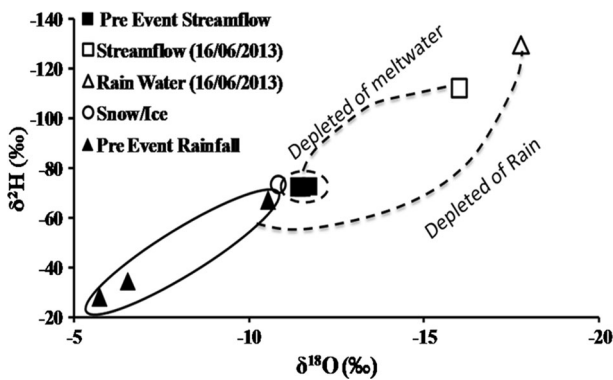


Fig. 5 Isotopic signature of rainfall, snow and river flow water during flash flood and pre-event (flood) storms

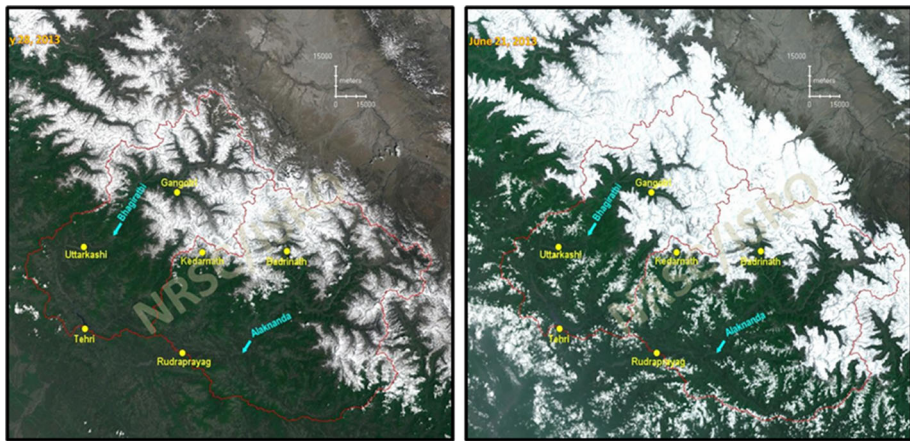


Fig. 6 Snow cover variation before and after the flash flood in the Mandakani catchment area, Central Himalaya, India (Source: NRSC report)

melt water isotopic signature in the head water region of Mandakani River. For the estimation of contribution of snow/ice melt water and rainfall-derived runoff on 6 and 16 June (flood day), signature of river water of 4 June was considered as melt water signature. No rainfall was recorded on 4 June 2013 in the automatic weather station (AWS) installed near the snout of glacier by the CFG, WIHG. On 4 June 2013, river isotopic signature ($\delta^{18}\text{O}$ and δD) are -11.39 and -69.36 ‰ and these are taken as snow/ice melt water isotopic signature for the estimation of contribution of rainfall runoff and snow/ice contribution. The observed rainfall amount on 6, 11 and 16 June are 27, 11 and 325 mm (Fig. 4). For 6 and 16 June 2013, observed rainfall amount was likely sufficient (>20 mm) for runoff generation in the river. But on 11 June, observed rainfall amount is very less and this amount may not be a contributing factor to the river discharge. Rainfall isotopic signatures of $\delta^{18}\text{O}$ for these dates are -5.73 and -6.53 ‰, whereas δD values are -27.79 and -34.47 ‰, respectively. Isotopic signatures of river water on 6, 11 June 2013 for $\delta^{18}\text{O}$ are -10.99 , -11.73 ‰, whereas for δD , these are -68.02 and -71.98 ‰.

Isotopic signature ($\delta^{18}\text{O}$ and δD) of rainfall for the flood day was -17.77 and -129.79 ‰, respectively. The signature of the rainfall of flood day is highly depleted as compared to rainfall occurred on 6 and 11 June 2013. Such a major variation in isotopic signature may be due to the heavy amount of rainfall (amount effect) (Kumar et al. 2010) or due to convection (Lakshmy et al. 2014) (Fig. 7). During the rain event, isotopically enriched vapour falls first and then residual vapour, which becomes isotopically depleted. Subsequent rains, while enriched with respect to the remaining vapour, are depleted with respect to earlier rains from the same vapour mass.

River water sample of the flood day shows -15.97 and -112.96 ‰ for $\delta^{18}\text{O}$ and δD , respectively, and shows depletion. Isotopic signature of river water on flood day also reflects that the contribution of rainfall is high in flash flood as river water signature is near to rain water signature of the flood day in head water region. Figure 5 shows that river was flowing with the signature of snow/ice melt runoff before the flood, whereas for the flood day, it was flowing with the signature of rainfall at base camp above Shri Kedarnath Temple. The d-excess of the rainfall and river water is also very near to each other for the flood day (Fig. 8).

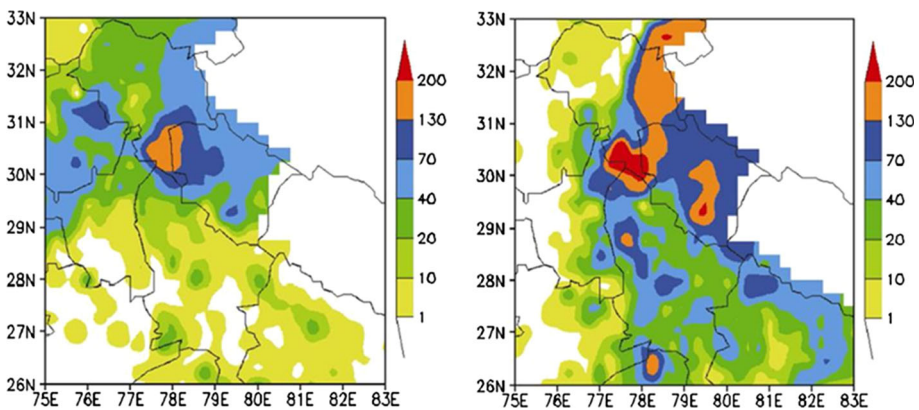


Fig. 7 Spatial distribution (resolution $0.25^\circ \times 0.25^\circ$) of rainfall (mm) activity during 16–17 June 2013 (Kotal et al. 2014)

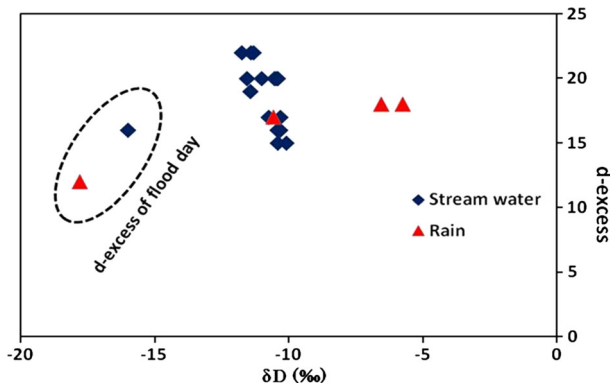


Fig. 8 Plot of d-excess versus $\delta^{18}\text{O}$ of river and rainfall at Chorabari base camp, Kedarnath valley, Central Himalaya, India

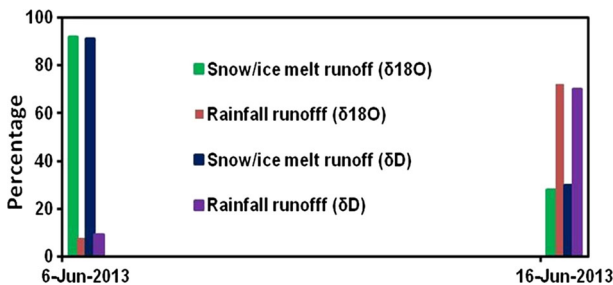


Fig. 9 Contribution of snow/ice melt runoff and rainfall-derived runoff to Mandakani River at Chorabari base camp above Shri Kedarnath Temple

An attempt was made to estimate the snow/ice melt runoff and rainfall runoff contribution in Mandakani River by using the two-component mixing model with oxygen and hydrogen isotopes for 6 and 16 June 2013. The contribution of snow/ice melt runoff is found 92 % (approximately), whereas contribution of rainfall-derived discharge is 8 % (approximately) by using oxygen isotope ($\delta^{18}\text{O}$) for 6 June 2013 in the river. Hydrogen isotope of the same sample shows the contribution of snow/ice melt runoff is approximately 91 % and the contribution of rainfall runoff approximately 9 % in the river.

For the 16 June 2013 (flood day), estimated contribution of rainfall-derived runoff is 72 %, whereas contribution of snow/ice melt runoff is 28 % by using oxygen isotope ($\delta^{18}\text{O}$) in the Mandakani River for the flood day. Hydrogen isotope is also used for the estimation of snow/ice melt runoff and rainfall-derived runoff in Mandakani River. It shows that about 70 % runoff contributed from rainfall-derived runoff and about 30 % runoff contribution is from snow/ice melt runoff in the Mandakani River above Shri Kedarnath Temple (Fig. 9). Results from both the isotopes ($\delta^{18}\text{O}$ and δD) corroborate each other. Heavy rainfall enhanced the melting of fresh snow due to which discharge volume of Mandakani River was increased and the flash flood occurred with the cumulative effect of rainfall and snowmelt.

7 Conclusion

This paper deals with the analysis of the available river water, rainfall and snow/ice melt samples to assess the causes of flash flood in Kedarnath region. Isotopic analysis of the samples indicates that the contribution of rainfall-derived runoff was high as compare to snow/ice melt runoff to the flash flood in Kedarnath region of Himalaya. But this flash flood appears to be the combined effect of rainfall-derived runoff and snowmelt runoff into the Mandakani River.

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