Kedarnath disaster: facts and plausible causes

Recent climate changes have had significant impact on high-mountain glacial environment. Rapid melting of snow/ice and heavy rainfall has resulted in the formation and expansion of moraine-dammed lakes, creating a potential danger from dammed lake outburst floods[1]. On 16 and 17 June 2013, heavy rains together with moraine dammed lake (Chorabari Lake) burst caused flooding of Saraswati and Mandakini Rivers in Rudraprayag district of Uttarakhand (Figure 1 *a*). Prolonged heavy down pour on 16 and 17 June 2013 resembled ‘cloud burst’ (except for amount of precipitation of 100 mm/h) type event in the Kedarnath valley and surrounding areas that damaged the banks of River Mandakini for 18 km between Kedarnath and Sonprayag, and completely washed away Gaurikund (1990 m asl), Rambara (2740 m asl) and Kedarnath (3546 m asl) towns. The roads and footpath between Gaurikund and Kedarnath were also damaged. There are reports of loss of large number of human lives and damage to the property and livestock. The Chorabari Lake (3960 m asl) also known as Gandhi Sarovar Lake is a snow melt and rain fed lake, located about 2 km upstream of Kedarnath town which is approximately 400 m long, 200 m wide having a depth of 15–20 m. The bursting of this lake led to its complete draining within 5–10 min as reported by the watch and ward staff of the Wadia Institute of Himalayan Geology (WIHG) who were present in WIHG camp at Chorabari Glacier on 16 June and early morning of 17 June 2013. The heavy rainfall together with melting of snow in the surrounding Chorabari Lake washed off both the banks of the Mandakini River causing massive devastation to the Kedarnath town. The WIHG meteorological observatory at Chorabari Glacier camp (3820 m asl) recorded 210 mm rainfall in 12 hours between 15 June (5:00 p.m.) and 16 June (5:00 a.m.) 2013. On 16 June 2013 alone (from 5:00 a.m. to 5:00 p.m.), 115 mm rainfall was recorded, causing 325 mm rain in 24 hours. WIHG has another rain gauge installed at its geophysical facility (MPGO) at Kopardhar near Ghuttu (30.53°N, 78.74°E; 1836 m asl), which is approximately 38 km (aerial distance) from Kedarnath. The Ghuttu rain gauge recorded 58 mm on 15 June, 121 mm on 16 June and 93 mm on 17 June with no rainfall on 18 June (Figure 2). The surface atmospheric pressure began to decrease on 15 June reaching a low (832.4 mB) on 17 June (Figure 2). During 15–17 June 2013, the heavy rains also caused devastation in other regions of Uttarakhand, Himachal and Nepal. The India Meteorological Department (IMD) linked heavy to very heavy rainfall on the higher Uttarakhand, Himachal and Nepal Himalaya to the convergence of the Southwest Monsoon trough and

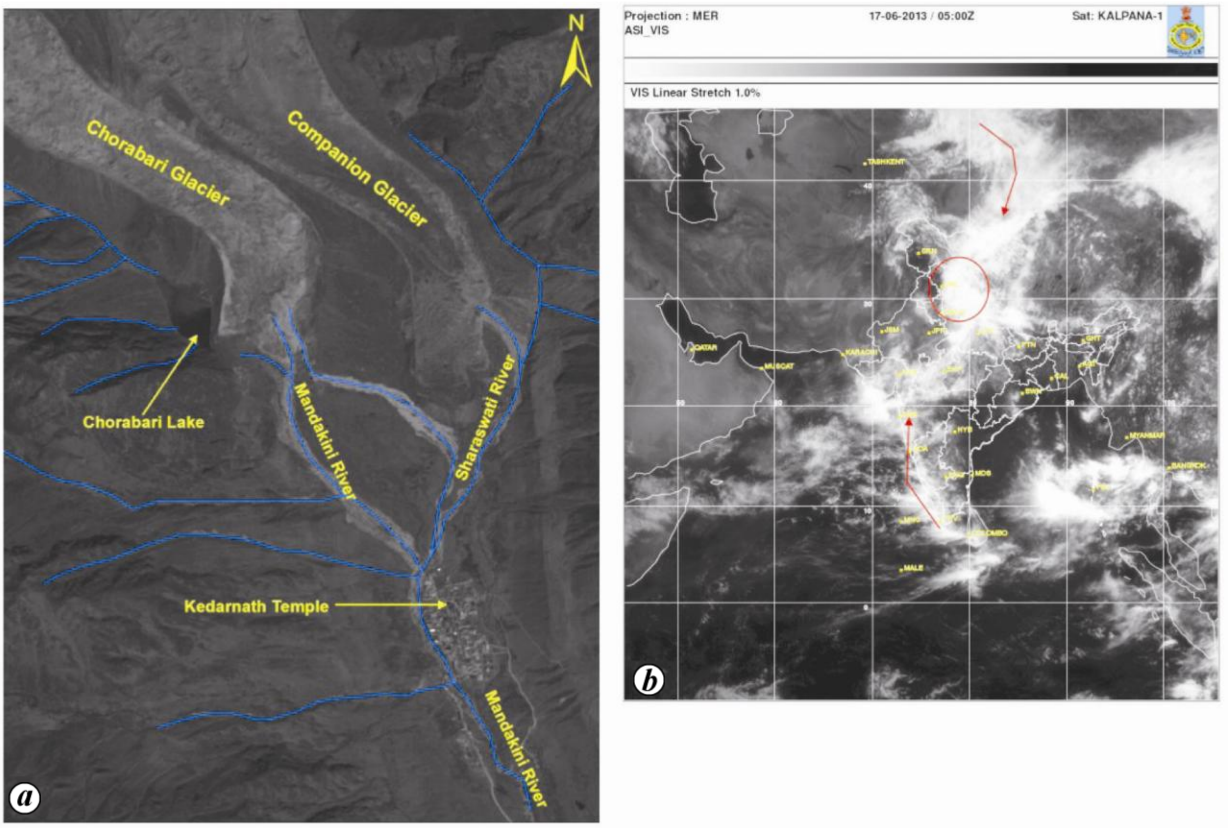

Figure 1. ***a***, Satellite view of Kedarnath area, showing drainage system, glaciers, lake and township[4]; ***b***, The India Meterological Department image (17 June 2013) suggested that the heavy rainfall on the higher Uttarakhand, Himachal and Nepal Himalaya caused the collision of the monsoon and westerly disturbance. Arrows (red colour) on the map indicate the moisture sources of the area. (Source: Figure 1 *b*: http://www.imd.gov.in/section/satmet/dynamic/insat.htm)

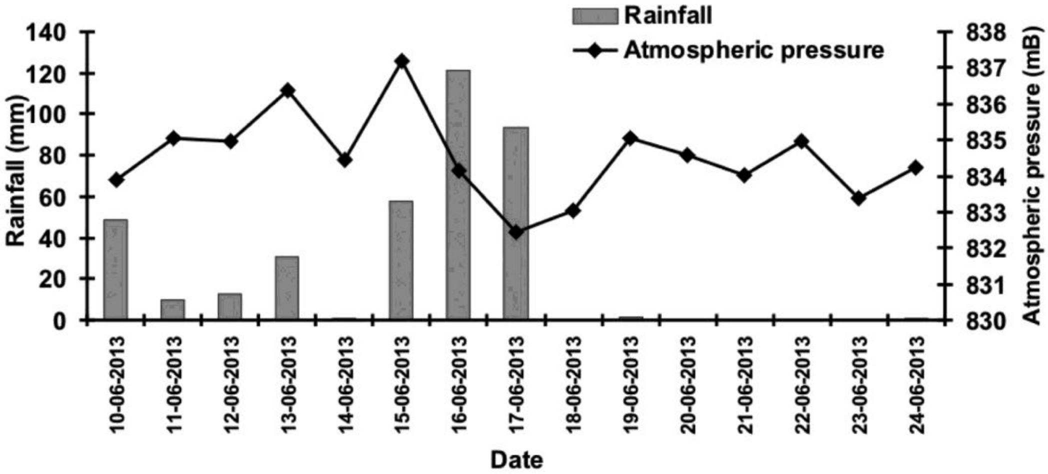

Figure 2. Rainfall and atmospheric pressure recorded at Kopardhar observatory near Ghuttu (WIHG), which is approximately 38 km (aerial distance) from Kedarnath.

Figure 3. Geomorphological setup of the Kedarnath area and view of settlement of the Kedarnath town along the river bank of Mandakini (May 2012 photo).

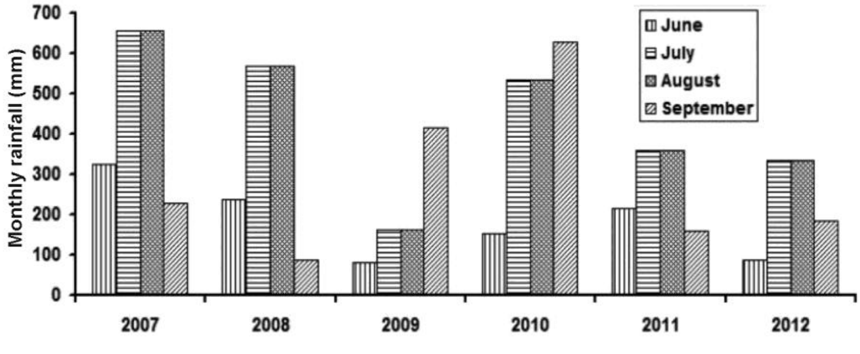

Figure 4. Histogram of summer rainfall pattern of the Kedarnath area during the period 2007 to 2012 AD. Maximum precipitation occurred during the rainy season from July and August[5].

westerly disturbances, which led to the formation of dense cloud over the Uttarakhand Himalaya (Figure 1 *b*).

The Kedarnath temple town is located in the western extremity of the Central Himalaya (30°44′6.7″N; 79°04′1″E) in the Mandakini River valley which has a total catchment area of ~67 km^2 (up to Rambara), out of which 23% area is covered by glaciers[2]. The catchment area is situated in the glacier modified U-shaped valley; the altitude ranges from 2740 to 6578 m asl. Such a variation in the altitude provides diverse landscape. Bhart Khunta (6578 m), Kedarnath (6940 m), Mahalaya peak (5970 m) and Hanuman top (5320 m) are few well known peaks in the area. Mandakini River originates from the Chorabari Glacier (3895 m) near Chorabari Lake (Figures 1 and 3) and joins Saraswati River which originates from Companion glacier at Kedarnath (Figure 3), passing through Rambara and Gaurikund. The Madhu Ganga and Dudh Ganga are the main tributaries that merge into the Mandakini River at Kedarnath town. Another equally important tributary of Mandakini River is Son Ganga which originates from Vasuki Lake (4040 m asl) and has a confluence with Mandakini River at Sonprayag (1709 m asl) which finally merges with Alaknanda River at Rudraprayag.

Geologically, the area north of the Pindari Thrust comprises calc silicate, biotite gneisses, schist and granite pegmatite apatite veins belonging to the Pindari Formation[3]. Above 3800 m asl altitudes, glacial processes dominate and between

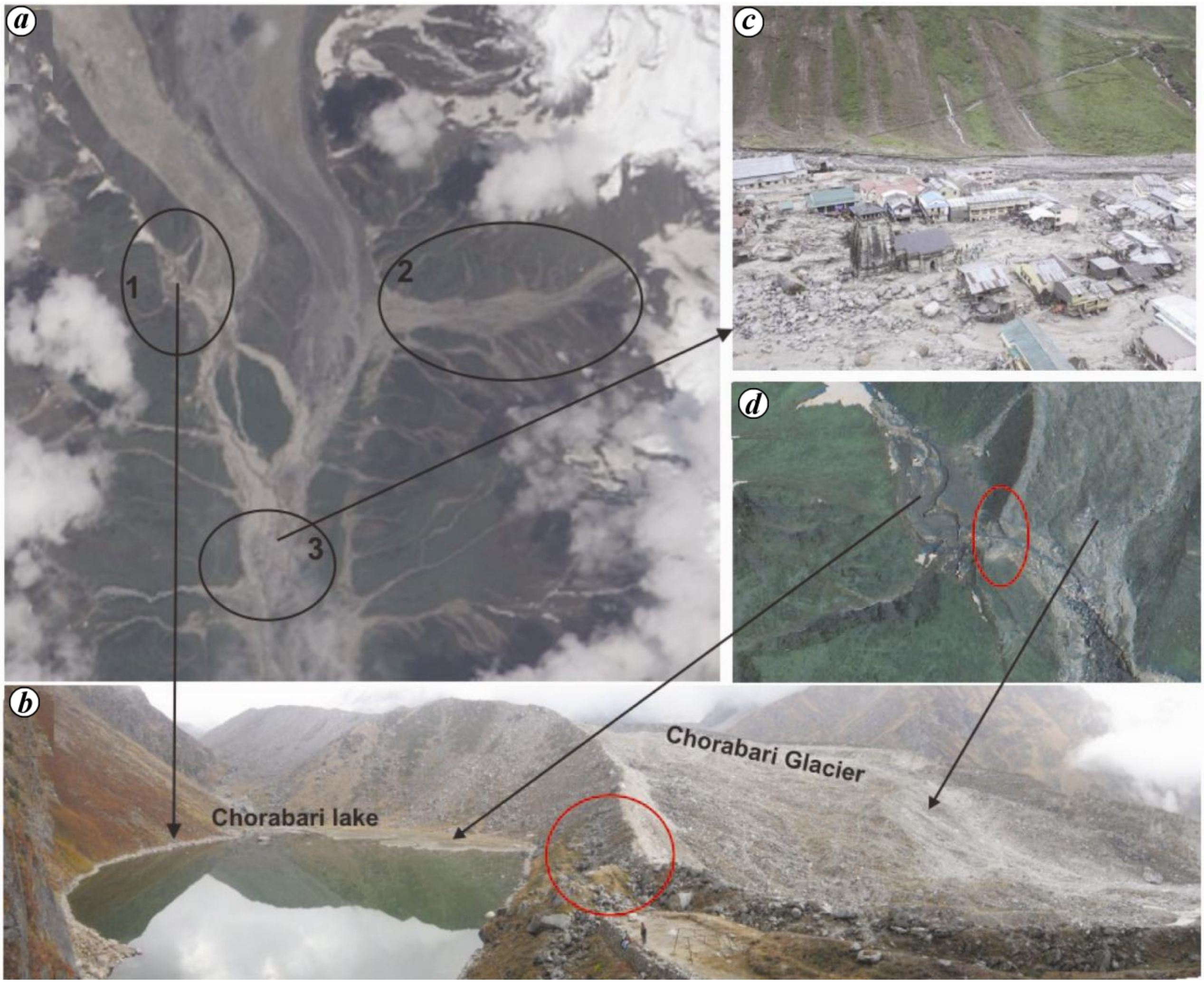

Figure 5. ***a***, The Landsat (8) satellite image (23 June 2013; after disaster), sowing the, lake burst (1), Gulleys erosion/cloud burst events (2) and circle (3) indicate the site of maximum devastation (http://blogs.agu.org/landslideblog/). ***b***, The panoramic view of Chorabari Lake and Glacier, the red circle indicate the weak zone of the lake, where the lake was burst. ***c***, The photograph showing the maximum devastation in Kedarnath town (Photo: Internet). ***d***, Cartosat image (Bhuwan) of post disaster of the Kedarnath and surrounding areas and clearly indicating Chorabari Lake outburst. The red circle indicates the breaching point of the Lake (http://bhuvan-noeda.nrsc.gov.in/projects/flood/#mappage).

3800 and 2800 m asl glaciofluvial processes are dominant; below 2800 m asl mainly the fluvial processes are active. Geomorphologically, Mandakini valley was formed by the erosional and depositional processes of glacio-fluvial origin. The Kedarnath town is situated on the outwash plane of Chorabari and Companion glaciers (Figure 3). The channels of Mandakini and Saraswati Rivers encircles this outwash plane and meet near the Kedarnath town where the outwash plane ends. These streams cut their banks every year. Overcrowding of the people near the temple led to a change in the course of Sarswati River which now flows just behind the Kedarnath town (Figure 3). Downstream near Rambara and Gaurikund the houses have been built on the old colluvial or fluvial deposits which are loose and prone to landslides and river cuttings.

Rainfall data from an automatic weather station (installed near the Chorabari snout) indicates that the Indian Summer Monsoon is the major source of precipitation (rainfall) in the study area with partial contribution from western disturbances during winter. Winter precipitation generally occurs between December and March when the western disturbances are dominant in the area as they move eastward over northern India. Total summer (JJAS) rainfall for each observation periods between 2007 and 2012 were 1685 mm, 1513 mm, 734 mm, 1662 mm, 1348 mm and 1115 mm for respective years. Based on the available rainfall data from our observatory at Chorabari glacier, the area received maximum precipitation during the rainy season, i.e. July and August (Figure 4).

The preliminary results suggest that the following two events caused devastation in the Kedarnath area of the Mandakini River basin.

Event 1

On 16 June 2013, at 5:15 p.m., the torrential rains flooded the Saraswati River and Dudh Ganga catchment area, resulting in excessive flow across all the channels. Following this very active erosion began in all the other gulleys causing excessive water and sediment accumulation in the major rivers (Figure 5 *a*). As a result, large volumes of water struck the town which simultaneously picked huge amount of loose sediment en route. The voluminous water studded with debris from the surrounding regions and glacial moraines moved towards Kedarnath town, washing off upper part of the city (Sankaracharya samadhi, Jalnigam guest house, Bharat Seva Sangh Ashram, etc.) and leading to the biggest ever devastation we have seen in the region. Our meteorological stations near Chorabari glacier recorded 325 mm rainfall at the base of the glaciers in two days on 15 and 16 June 2013. Due to heavy downpour, the town of Rambara was completely washed away on 16 June evening.

Event 2

The second event occurred on 17 June 2013 at 6:45 a.m., after overflow and collapse of the moraine dammed Chorabari Lake (Figure 5 *a* and *b*) which released large volume of water that caused another flash flood in the Kedarnath town leading to heavy devastation downstream (Gaurikund, Sonprayag, Phata, etc.). Our study shows that the main cause of the Chorabari Lake collapse was torrential rains that the area received between 15 and 17 June 2013. Due to heavy rainfall the right lateral basin of the glacier, which is thickly covered by snow (>7 feet thick near the upper part of lake during field work on 4 June 2013) rapidly melted due to rainwater allowing large amount of water accumulation in the Gandhi Sarovar lake (Figure 5 *b*). There were no outlets in the lake, the water was simply released through narrow passages at the bottom of the lake. Suddenly millions of gallons of water accumulated in the moraine dammed lake within 3 days, which increased their potential energy and reduced the shear strength of the dam. Ultimately the loose-moraine dam breached causing an enormous devastation in the Kedarnath valley (Figure 5 *a*, *c* and *d*).

Recently, the risk of natural disasters has increased in the area as a result of increasing anthropogenic activities (Figure 3). This trend is likely to increase in future as the activities like pilgrimage, tourism, etc. will increase. The natural flow paths of the channels get obstructed due to the construction of man-made structures that results in deviation of the flow from its natural course. Apprehending the tendency of increasing urbanization due to increase in the number of pilgrims, tourists and other developmental activities in the area, selection of safe land-use locations would be a formidable task to accomplish. However, the Government has to take care of these issues in future rebuilding of the devastated area, though the task of rehabilitation of the displaced population is enormous.

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