

Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition

Abstract Heavy rainfall in June 2013 triggered flash flooding and landslides throughout the Indian Himalayan state of Uttarakhand, killing more than 6000 people. The vast majority of fatalities and destruction resulted directly from a lake outburst and debris flow disaster originating from above the village of Kedarnath on June 16 and 17. Here, we provide a systematic analysis of the contributing factors leading to the Kedarnath disaster, both in terms of hydro-meteorological triggering and topographic predisposition. Topographic characteristics of the lake watershed above Kedarnath are compared with other glacial lakes across the north-western Himalayan states of Uttarakhand and Himachal Pradesh, and implications for glacier lake outburst hazard assessment in a changing climate are discussed. Our analysis suggests that the early onset of heavy monsoon rainfall (390 mm, June 10–17) immediately following a 4-week period of unusually rapid snow cover depletion and elevated streamflow was the crucial hydrometeorological factor, resulting in slope saturation and significant run-off into the small seasonal glacial lake. Between mid-May and mid-June 2013, snow-covered area above Kedarnath decreased by around 50 %. The unusual situation of the lake being dammed in a steep, unstable paraglacial environment but fed entirely from snowmelt and rainfall within a fluvial dominated watershed is important in the context of this disaster. A simple scheme enabling large-scale recognition of such an unfavourable topographic setting is introduced. In view of projected 21st century changes in monsoon timing and heavy precipitation in South Asia, more emphasis should be given to potential hydrometeorological triggering of lake outburst and debris flow disasters in the Himalaya.

Keywords Glacial lake outburst · Rainfall · Snowmelt · Disaster · Himalaya

Introduction

Flood and landslide disasters are common in the Himalayan states of northern India, owing to the unfavourable interaction of climate, lithology, topography and seismicity (Nadim et al. 2006). Heavy rainfall in June 2013 triggered numerous mass movements across the state of Uttarakhand, including two large debris flows on June 16 and 17 which devastated the village of Kedarnath, and the settlements of Rambara and Gaurikund located further downstream (Das et al. 2015; Dobhal et al. 2013a; Martha et al. 2014). Throughout the region, flash flooding and landslides killed more than 6000 people (Guha-Sapir et al. 2014) of which the vast majority were associated with the Kedarnath disaster. Countless roads and bridges were damaged, and at least 30 hydropower plants were either destroyed or severely damaged (Sati and Gahalaut 2013). The destruction of roads and trekking routes left around 100,000 pilgrims and tourists stranded until military and civic authorities could complete evacuation efforts (Martha et al. 2014).

In contrast to other significant flood and landslide disasters occurring in the Indian Himalayan states over the past century (e.g. Guha-Sapir et al. 2014), the Kedarnath disaster is the only high-fatality event known to these authors that has originated from within a glaciated environment and has included failure of a small moraine dammed lake. Almost immediately following the disaster, the source areas and flow paths that devastated Kedarnath and downstream villages were reconstructed from remotely sensed imagery and available first-hand reports (Petley 2013). Subsequent scientific attention has largely focused on understanding the extreme rainfall triggering event (Dubey et al. 2013; Joseph et al. 2014; Singh et al. 2014), reconstructing flood volumes and discharge (Das et al. 2015; Durga Rao et al. 2014) or discussions surrounding the important human aspects of the disaster, such as development and land use practices, physical and societal vulnerabilities and the government response to the disaster (Chand 2014; Sati and Gahalaut 2013; Uniyal 2013). Given that the heavy monsoon rain arrived earlier than normal, some authors have alluded to the role of rain-on-snow-type melting enhancing run-off and contributing to ground saturation and breaching of the lake (Arora et al. 2014; Dobhal et al. 2013a), with suggestions that June snow cover may even have been thicker than normal (Durga Rao et al. 2014; Martha et al. 2014; Singh et al. 2014). However, snow cover evolution leading up to the disaster has not yet been analysed, and a complete assessment of the hydro-meteorological triggering factors (rainfall, temperature and snow-melt) is still lacking.

There have been over 2000 glacial lakes mapped across the Himalaya (Fujita et al. 2013). Despite glacial lake outburst floods (GLOFs) predominating during the peak monsoon months, there have been no unequivocal documented incidents of hydrometeorologically triggered outbursts over the past century (ICIMOD 2011; Richardson and Reynolds 2000). Even globally, such incidents are rarely evidenced (Clague and Evans 2000; O'Connor et al. 2001; Worni et al. 2012), with many studies documenting that primarily avalanche and landslide impact triggered outburst floods (Vilimek et al. 2013). Hence, the Kedarnath disaster has potential regional and global significance in this regard. Surprisingly therefore, no attention has been given to the characteristics of the lake and its catchment area that may have contributed towards the enhanced run-off into and catastrophic breaching of this lake. Important questions remain as to why this particular lake became problematic and whether or not similar scenarios may unfold at other lakes in the future. Were there topographic and hydrological characteristics of this lake and its watershed that made it more susceptible than others, and more importantly, can these characteristics be captured within large-scale GLOF hazard inventories? To address these questions, we aim to provide here a coherent and systematic analysis of the contributing factors leading to the Kedarnath lake outburst flood,

both in terms of hydrometeorological triggering and topographic predisposition. In view of the large number of glacial lakes in the Himalaya, topographic characteristics at Kedarnath are compared with other glacial lakes across the north-western Himalayan states of Uttarakhand (UK) and Himachal Pradesh (HP), and implications for GLOF hazard assessment in a changing climate are discussed.

Geological and geomorphic setting

The village of Kedarnath is of great importance and significance to the Hindu faith, with the village temple visited daily by thousands of pilgrims during the summer months. The village is situated at the head of the Mandakini river valley, on a glacio-fluvial outwash plain of the Chorabari and Companion glaciers (3580 m a.s.l.) (Fig. 1). A large medial moraine separates the two glacial tongues, suggesting they may once have formed a single entity (Dobhal et al. 2013a). The highest surrounding peaks include Bhartkhunta peak (6578 m a.s.l.) and Kedarnath peak (6940 m a.s.l.). Lateral moraines are observed some 6 km further downstream in Rambara, indicating the maximum extent of the Chorabari Glacier around 13 ka BP, attributed to cooler summer temperatures and increased monsoon precipitation at that time (Mehta et al. 2012). Younger moraines near the Kedarnath temple were formed approximately 5 ka BP, and no evidence exists that the glacier has readvanced since this time. The temple dates back to at least 3000 BP and in itself provides evidence that the area upon which the village is now located was not affected by Little Ice Age glacier readvancement (Mehta et al. 2012). Recent field measurements reveal that the Chorabari and Companion glacier complex has lost some 11 % of its total surface area over the period 1962–2010, and the average magnitude of mass loss ($4.4 \times 10^6 \text{ m}^3 \text{ w.e.a}^{-1}$) over the period 2003–2010 is higher than has been recorded previously for other glaciers in the region (Dobhal et al. 2013b). Geologically, the area comprises calc silicate, biotite gneisses, schist and granite pegmatite apatite veins belonging to the Pindari Formation (Valdiya et al. 1999). Permafrost may exist within the Mandakini catchment at elevations above approximately 4500 m a.s.l. (Gruber 2012), but there is no evidence to suggest that permafrost was a relevant factor in the Kedarnath disaster. According to Dobhal et al. (2013a), the Mandakini and Sharaswati rivers have frequently overflowed their banks, so that the path of the Sharaswati River has been diverted by a series of engineering structures to join the Mandakini River on the western side of the village and to mitigate the flood hazard from the rivers encircling the village (Fig. 1).

Methodology and data sources

Our approach integrates (i) a local reconstruction of the hydrometeorological conditions (rainfall, temperature, snowmelt) which preceded the Kedarnath disaster, with (ii) a broader GIS-based topographic assessment of glacial lake watershed characteristics across the states of UK and HP. In view of limited data availability and access often associated with high-mountain disasters, our approach is largely based on methods and data sources which can be readily applied across other remote regional settings.

Hydrometeorological analyses

Hydrometeorological data could not be obtained directly from the Kedarnath area for this study, and we therefore utilize a

combination of nearby measurements and remotely sensed data. Precipitation is estimated across the states of UK and HP from the Tropical Rainfall Measuring Mission (TRMM), using version 7 of the research derived daily precipitation rates (3B42 V7 derived). For time series analyses in the period leading up to the Kedarnath disaster, data is extracted for the 0.25° ($\sim 25 \text{ km}$) grid cell containing the village, Chorabari Lake and the southernmost area of the upstream watershed, providing the most appropriate representation of conditions in this wetter area on the southern side of the Himalaya (Dubey et al. 2013). Both underestimation and overestimation of TRMM-derived precipitation is reported for different states of India, but in general, TRMM 3B42 is considered a valuable source of information in view of the lack or scarcity of ground-based rainfall measurements (Mathew et al. 2014). For the June 2013 rainfall event, TRMM data enables a longer term perspective (with data extending back to 1998), but where possible, our analyses are compared with published ground-based rainfall measurements covering the period of the disaster. Station-based air temperature and river discharge data for the period 2000–2013 is taken from near the snout area of the Gangotri Glacier (3800 m a.s.l., $\sim 20 \text{ km}$ north of Kedarnath), in a well-established measurement program operated by the National Institute of Hydrology (NIH; Arora et al. 2014).

In order to reconstruct and quantify the changes in snow cover preceding the Kedarnath disaster, Moderate-Resolution Imaging Spectroradiometer (MODIS)-derived snow cover data was extracted for the catchment area above the village of Kedarnath ($\sim 40 \text{ km}^2$). We used the MODIS/Terra Snow Cover 8-Day product (MOD10A2, algorithm version 5, 500 m resolution) which provides a large-scale snow cover record extending from 2000 to 2013. As a first step, all MODIS images were reprojected into the local UTM 43 N projection. Although the accuracy of MODIS 8-day snow cover products is generally considered to be high (Hasson et al. 2014; Immerzeel et al. 2009), problems arise from the presence of clouds because it may be misclassified as snow or simply hides the full extent of the snow-covered terrain (Hall et al. 2002). For example, Hasson et al. (2014) found that for the Indus river catchment, MODIS slightly overestimated the snow cover during the spring and summer seasons due to higher cloud coverage and underestimated snow cover during the autumn season. To avoid unrepresentative snow cover values due to cloud coverage, we therefore excluded all dates (eight datasets) where the cloud cover was higher than 50 % within the catchment area above Kedarnath. To establish the snow line altitude for the catchment, a digital elevation model (ASTER GDEM—see section “Assessment of glacial lake topographic disposition”) was resampled from 30 to 500 m, classified into 100 m elevation bands and intersected with the MODIS images. The lowest elevation band where snow cover is found to be higher than 50 % is then exported as the snow line altitude for the respective date.

Assessment of glacial lake topographic disposition

A new glacial lake inventory was developed for the states of UK and HP (updated from Worni et al. 2013). Glacial lakes were detected from 2013 and 2014 Landsat 8 imagery using the normalized difference water index applied to the blue and near-infrared spectral channels (after Huggel et al. 2002), which express maximum and minimum reflectance differences for glacial water and give good discrimination from ice and snow. Following the

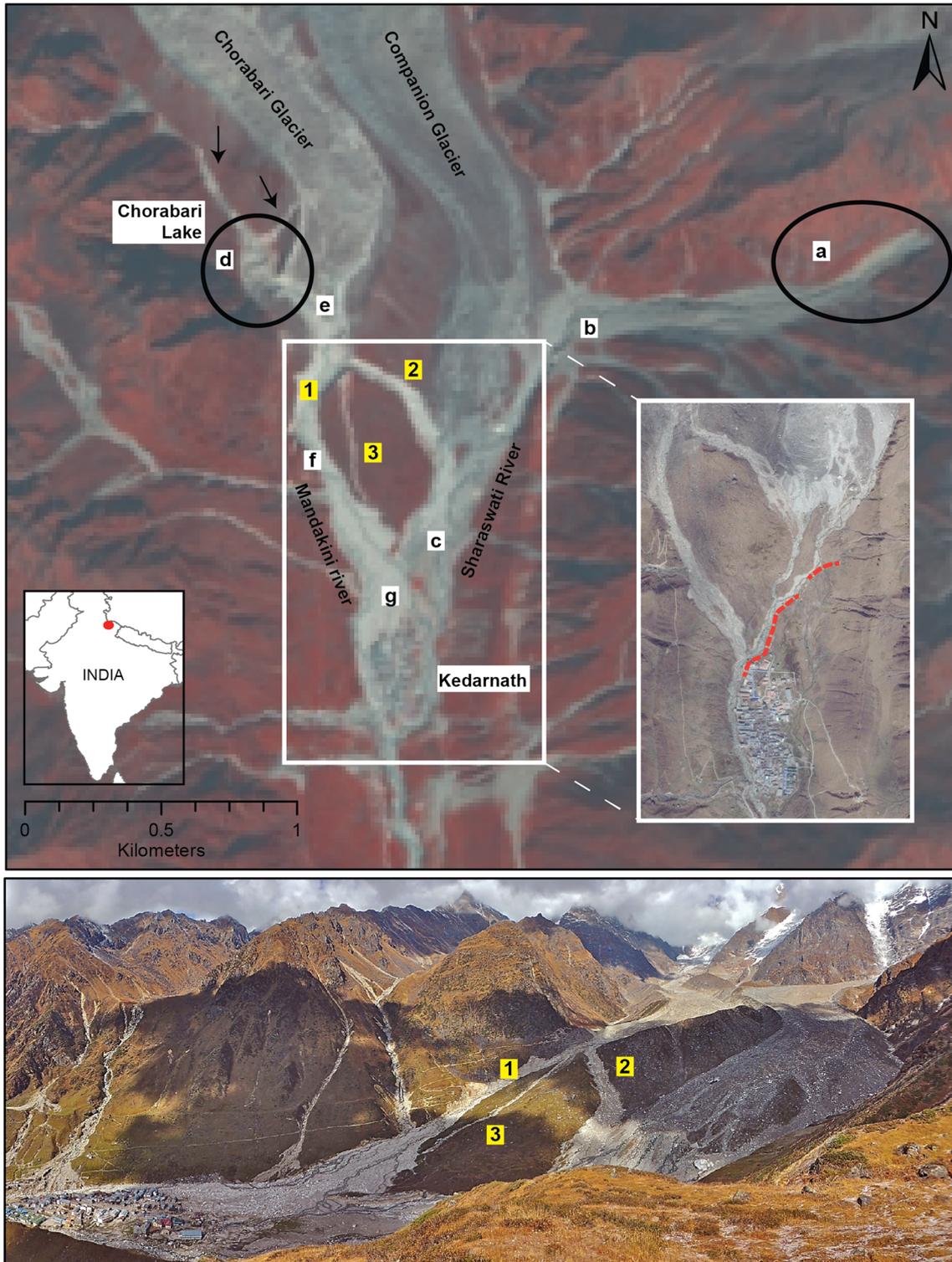


Fig. 1 Overview of the Kedarnath disaster (*top*), showing origin of debris flows on June 16 (noted *a*) and June 17 (noted *d*). See text for further details on annotated features. The Landsat 8 false-colour base image is from September 22, 2013. The pre-disaster inset image is from Bing maps, with the *red line* indicating the engineering structures designed to divert the Sharaswati River around to the western side of Kedarnath. (*bottom*) Post-disaster image looking north-west across the devastation of Kedarnath towards Chorabari Lake (photo: Vaibhav Kaul)

automated removal of misclassifications in areas of shadow and a manual quality check, 169 lakes larger than 0.01 km² were identified across the two states (neighbouring lakes within 10 km of the

state borders were also included). A broad classification of glacial lakes was applied (based on ICIMOD 2011), including lakes that may not be directly dammed by glacial processes but are situated

within a glaciated valley and are at least partially fed by glacial meltwater.

The watershed area and related hydrotopographic parameters for Chorabari Lake, and all other glacial lakes, were calculated using the hydrology and surface analytical suite of ArcGIS tools and topography obtained from the global digital elevation model (GDEM) version 2 of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Based on imagery obtained between the years 2000 and 2007, the ASTER GDEM is produced at a horizontal resolution of 1 arc-second (~ 30 m) and has an assessed vertical (root-mean-squared error) of around 17 m (ASTER GDEM Validation Team 2011). An important component of this study is the additional distinction of the ice-free area within the lake watershed ($WS_{ice-free}$) and the proportion of the total watershed which drains directly into the glacial lake (WS_{dir}) (i.e. where rainfall or snowmelt can run off directly into the glacier lake without travelling via the glacial hydrological system). For this distinction, glacier masks were obtained from Barjarcharya et al. (2014) and Frey et al. (2012). To determine WS_{dir} , glacier areas were treated as artificially large sinks with no possible connectivity to the lakes. The ArcGIS flow direction and watershed routines were then run on this modified DEM.

Event reconstruction

Within a few weeks after the disaster at Kedarnath, a detailed first reconstruction was published in an internet blog associated with the American Geophysical Union, drawing upon media and local witness reports, and available earth imagery at that time (Petley 2013). This early account generally concurs with a published report from the Wadia Institute of Himalayan Geology, who had scientists stationed on the glacier above the village when the disaster struck (Dobhal et al. 2013a), and with a more recent elaborated regional overview (Martha et al. 2014). Drawing upon these first reconstructions, and additional interpretation of earth imagery, a succinct summary of the June 16 and 17 events is provided here.

June 16 debris flow

Local reports indicate that surface flooding, erosion and damage in the villages of Kedarnath and Rambara was already evident by the afternoon of June 16, following 2 days of heavy rainfall (Sengupta 2013). At around 7 pm that evening, the first substantial debris flow struck Kedarnath, thought to have originated from a shallow landslide on steep slopes (25° – 35°) high above the terminus of the Companion Glacier (~ 4250 m a.s.l., a in Fig. 1) (Martha et al. 2014; Petley 2013). A large amount of debris was entrained as the flow moved downslope through an actively eroding snow and debris avalanche channel (b in Fig. 1) and over steep moraine and outwash gravels at the eastern margin and proglacial area of the glacier. Engineering structures designed to divert the Sharaswati around to the western side of the Kedarnath village were overwhelmed, and a significant portion of the debris flow followed the former course of the river to impact the north-eastern edge of the village (c in Fig. 1) and continued downstream where the village of Rambara was inundated.

June 17 lake outburst flood and debris flow

The second and most catastrophic debris flow initiated at around 6.45 am the following morning (Dobhal et al. 2013a), resulting

from the breach of the small seasonal lake formed in a depression at the outside margin of the Chorabari western lateral moraine (d in Figs. 1 and 2). Known as Chorabari or Gandhi Sarovar Lake, the lake was approximately 400 m long by 200 m wide (Dobhal et al. 2013a), with maximum depths calculated in the range of 11 to 15 m (Das et al. 2015) (Fig. 2). The lake had no direct contact with the glacier and was fed exclusively by run-off from rainfall and snowmelt. The lake had an estimated maximum volume of around $0.4 \text{ m}^3 \times 10^6$ (Das et al. 2015; Durga Rao et al. 2014) and no outlet channel. In addition to infilling from run-off, there is evidence that debris was transported into Chorabari Lake directly from the sounding moraine wall and from upstream where substantial new erosion is visible in post-disaster imagery (see arrows in Fig. 1). The combined volume of water and debris accumulating in the lake led to catastrophic breaching at a low point in the surrounding moraine wall (Fig. 2a). Field reports and image analysis suggests that the moraine damming the lake was overflowed by the rising water level initiating a progressive erosion process that eventually resulted in a full breach of the moraine, similarly as reported from other cases (e.g. Worni et al. 2012). Further sediment has been entrained as the debris flow travelled across the terminus of the debris covered glacier, where slope exceeds 10° for much of the path (Fig. 3) and where pooling surface water forms in flatter areas. From this point, the flow separated into two main and one secondary paths which converged just above Kedarnath: (1) A main component turned south to follow the very steep channel of the Mandakini River directly towards Kedarnath (f in Fig. 1). Substantial erosion is visible in the ~ 400 m steepest section of this channel, where slope gradients exceed 20° (Fig. 3). Some of this flow remained confined to the main river channel towards the west of the village, but clearly a large and destructive component of the flow entered directly into the village (g in Fig. 1). (2) A second large component passed through an existing steep channel in the medial moraine separating the two glacier tongues, turning south as the path reached the proglacial area of the Companion Glacier, to continue along the Sharaswati River towards Kedarnath. (3) A third smaller path is visible where an old channel was reactivated within the vegetated moraine separating the two main paths but does not appear to have added to the mass which inundated the village. Significant erosion and devastation from this event were observed some further 20 km down the Mandakini river valley.

Hydrometeorological analyses

Dobhal et al. (2013a) reported 325 mm of rainfall at a meteorological station installed on Chorabari Glacier in the 24 h between 5 pm June 15 and 5 pm June 16. Long-term ground-based records are not available, but TRMM data since 1998 confirms that the precipitation experienced in the days immediately preceding the disaster was very unusual for this time of year (Table 1, Fig. 4). As an area averaged quantity, the magnitude of the TRMM measured precipitation is considerably less than that measured directly on the Chorabari Glacier. However, for the total June 15–17 TRMM precipitation event (212 mm), there is closer agreement with the magnitudes observed at Kopardhar, ~ 38 km south-west of Kedarnath (271 mm) (Dobhal et al. 2013a), while considerably less precipitation was observed only 20 km to the north at Gangotri Glacier (166 mm) (Arora et al. 2014). The total June 16 and 17 TRMM-derived precipitation over the Kedarnath catchment of

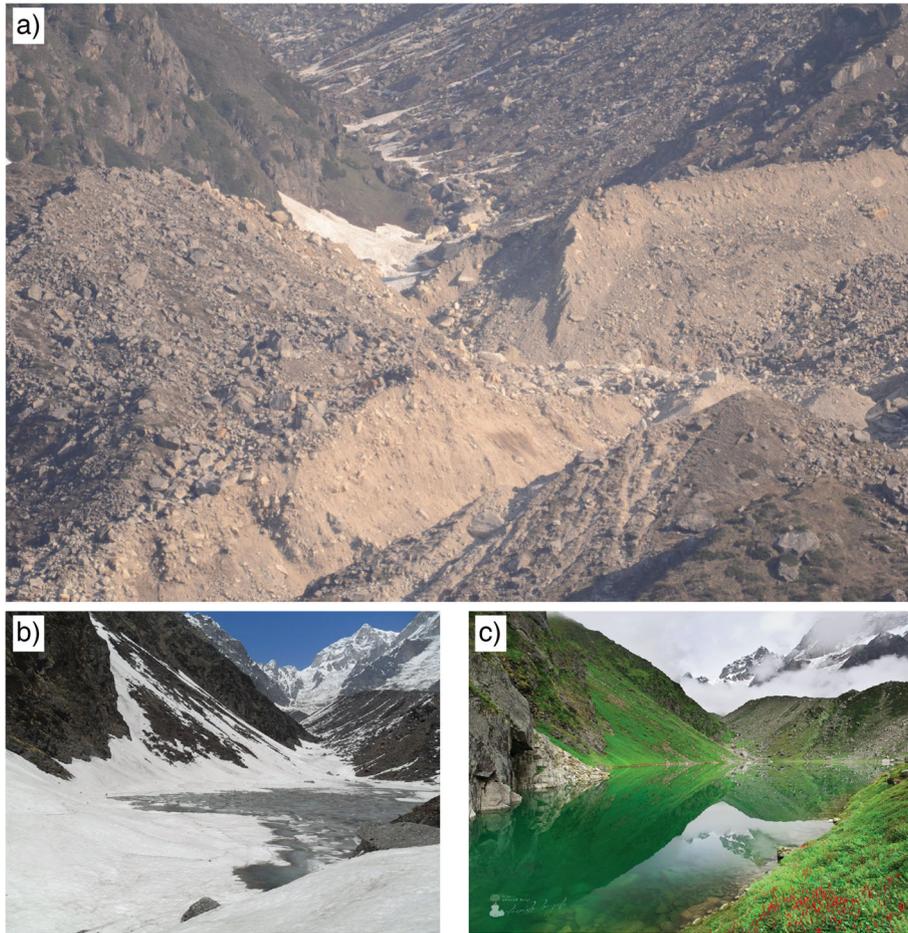


Fig. 2 a View towards the dam breach that enabled the catastrophic outburst flood from Chorabari Lake on June 17, 2013 (image taken June 7, 2014 by D. Grossman). Images from previous years show the former lake b developing in spring and c at normal summer extent (images are from www.merapahadforum.com and www.dineshhegde.wordpress.com)

162.8 mm compares well with the Rudraprayag district-wide average of 180 mm reported by the Indian Meteorological Department (IMD 2013).

Although most reports have focused on the exceptionally heavy precipitation beginning on June 15 and peaking on June 16 and 17, the TRMM data reveals a precursory large 145 mm event some days earlier on June 10 and 11 (Table 1, Figs. 4 and 5) (see also

Durga Rao et al. 2014; Martha et al. 2014). Although it remains unreported how much precipitation from this event was directly measured on Chorabari Glacier, some 60 mm was measured at Kopardhar (Dobhal et al. 2013a). Both the June 10–11 and June 15–17 precipitation events were of a magnitude that had not previously been measured during this time of year within the 15-year TRMM period of record (Fig. 4). The heavy monsoon rains

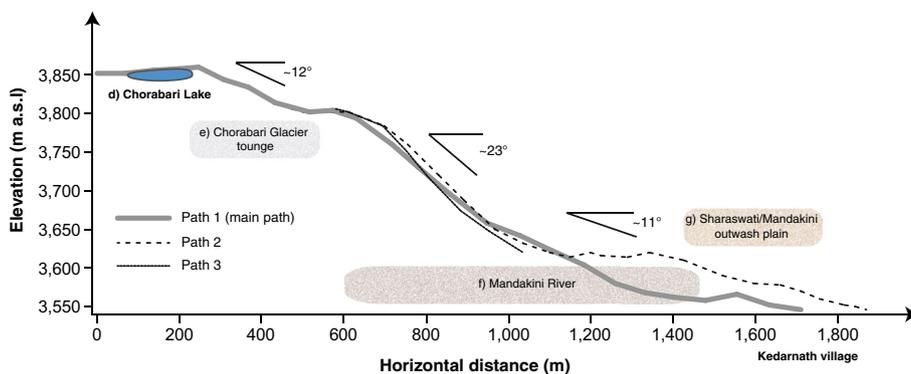


Fig. 3 Profile of the June 17 lake outburst and initial debris flow paths above Kedarnath. Slope angles are indicated for the main debris flow path (path 1 in Fig. 1). Annotations (d–g) relate to locations shown in Fig. 1

Table 1 TRMM rainfall measured over the Kedarnath catchment area in the days leading up to the June 16 and 17, 2013 disaster

	Total rainfall (TRMM derived)	15-year anomaly (TRMM derived)
10 June	59.1 mm	+55 mm
11 June	85.5 mm	+82 mm
12 June	19.0 mm	+15 mm
13 June	9.5 mm	+6 mm
14 June	6.6 mm	+2 mm
15 June	48.9 mm	+44 mm
16 June	104.4 mm	+100 mm
17 June	58.4 mm	+53 mm
Total rainfall period	391.4 mm	+358 mm

Anomalies are with respect to the precipitation mean of a 5-day moving window centred on the given date, in the preceding years 1998–2012

normally arrive 2–3 weeks later in early July, but even during the peak monsoon period, such magnitudes appear only rarely (exceeding the 90th percentile), although are not unprecedented (Fig. 4).

While TRMM shows the June 10–11 precipitation event to have been reasonably evenly distributed across the states of UK and HP, the larger June 15–17 event was centred on western UK and shows a clear decrease in precipitation towards the dryer areas in the north-west, lee of the Garwal Himalayan range (Fig. 5). Specifically, in regards to the June 17 lake outburst event, it should therefore be noted that Chorabari Lake above Kedarnath is located among a relatively small grouping of glacial lakes situated towards the southern side of the Garwal Himalaya, within the zone of heaviest rainfall.

The onset of heavy precipitation on June 15 was associated with a rapid drop in air temperature (Fig. 6). At Gangotri Glacier snout (~20 km north of Kedarnath, 3800 m a.s.l.), mean temperatures dropped to an unusually cold 1.6 °C by June 17. Assuming a moist adiabatic lapse rate of 5.5 °C km⁻¹, we can estimate a corresponding drop in the freezing level from ~5650 m a.s.l. at the beginning of the precipitation event, down to 5000 m a.s.l. on June 16 and

finally 4100 m a.s.l. by June 17. Hence, rainfall would have predominated within the source area of the June 16 debris flow and within the watershed area of Chorabari Lake throughout most of the period of heavy precipitation. Temperatures could have enabled some significant snowfall towards the end of the period only.

A less explored aspect of the Kedarnath disaster, and particularly the catastrophic breach of Chorabari Lake, is the role of snowmelt and its contribution to run-off. From discharge data recorded at Gangotri Glacier, it is evident that streams in the region were flowing at unusually high levels for several weeks before the onset of the heavy rains in mid-June (Fig. 7). This suggestion of an unusually high run-off contribution from melting of the seasonal snowpack is supported by MODIS-derived snow cover mapping in the Kedarnath catchment over this same time period (Figs. 8 and 9). Over a 4-week period, the snow-covered area decreased nearly 50 %, from above average coverage in mid-May to well below average coverage by the second week of June (Fig. 8). Such a rapid decrease has not been observed in the previous 13-year MODIS record, where the average decrease in snow-covered area over the same 4-week window is only 15 %. Snowline elevations rose from around 4000 to 5000 m a.s.l. over

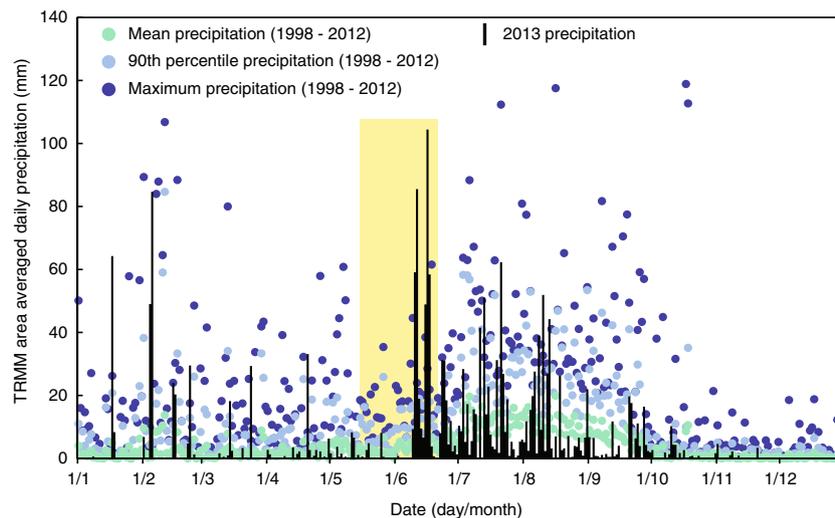


Fig. 4 TRMM area averaged daily precipitation over Kedarnath. Daily measurements during 2013 are compared to the longer term (1998–2012) mean, maximum and 90th percentile values. The 4-week period preceding and including the June 16–17 debris flow/lake outburst disaster is highlighted (yellow shading)

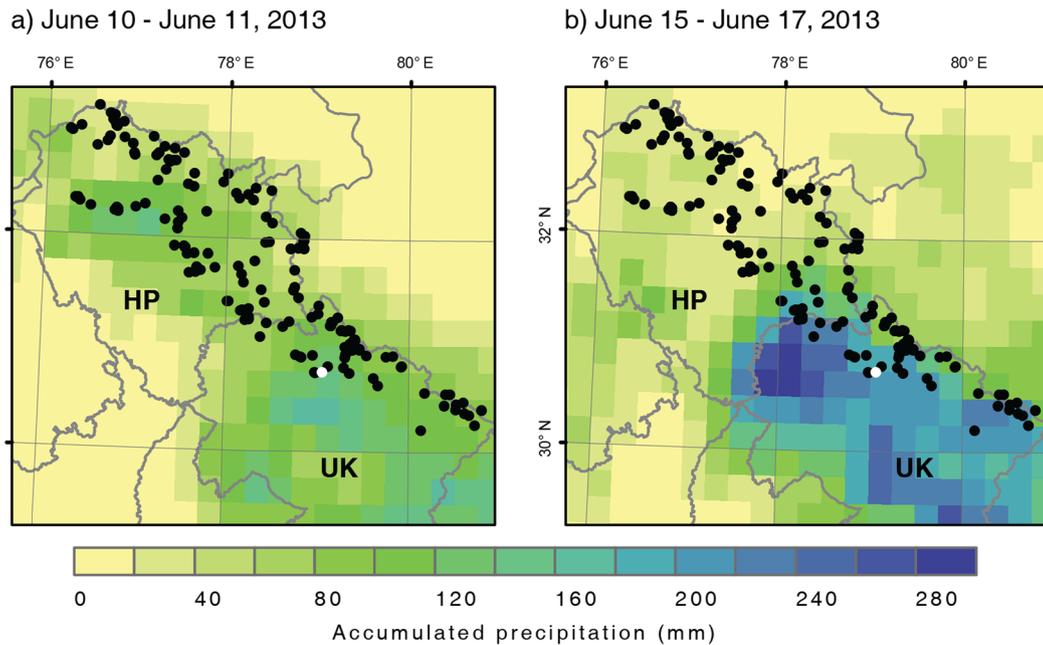


Fig. 5 TRMM accumulated precipitation over the states of Uttarakhand (UK) and Himachal Pradesh (HP) for the periods a June 10–11, 2013 and b June 15–17, 2013. Circles indicate glacial lakes, with Chorabari Lake highlighted in white

this same time period, although avalanche snow and other smaller snow patches (not captured by MODIS) remained at lower elevations, including within the watershed area of Chorabari Lake (Fig. 9). The onset of this period of rapid snow cover depletion appears to have coincided with unusually warm temperatures in mid-May to late May (Fig. 6). A notable and unusual increase in snow-covered area from June 17 is consistent with the aforementioned cooling of temperatures, bringing snowfall towards the end of the June 15–17 heavy precipitation event.

Glacial lake topographic disposition

Despite rainfall and snowmelt previously being recognized as major factors in GLOF events (Clague and Evans 2000; O'Connor et al. 2001; Worni et al. 2012), regional scale approaches to GLOF hazard assessment have rarely considered relevant topographic factors that might predispose a given lake catchment to fast run-off and lake infilling during unusual hydrometeorological events. Watershed area is considered a proxy for basin discharge potential, providing an important controlling factor for the longevity of

landslide dammed lakes (Korup 2004) and has been included as a relevant factor in some GLOF assessment schemes (Huggel et al. 2002; McKillop and Clague 2007). The unusual aspect of Chorabari Lake, however, is not the absolute size of the watershed but rather the fact that the watershed is entirely free of glacier ice, and therefore, the lake is seasonal in character and fed from snowmelt and rainfall only. This characteristic is parameterized herein as the nonglacial watershed (WS_{ng}) component and is quantified as a dimensionless value on the basis of (1) the ice-free area of the watershed ($WS_{ice-free}$) multiplied by (2) the proportion of the total watershed area that drains directly into the glacial lake (WS_{dir}) (see also section “Methodology and data sources”). In this way, unfavourable topographic disposition rankings are assigned to catchments such as Chorabari, which not only contain a large ice-free area but also where a large proportion of the run-off is able to drain directly into the lake, rather than via the generally more complex and slower glacio-hydrological system. Additional parameters assessed here which further characterize the drainage capacity of a watershed include stream size, drainage density and

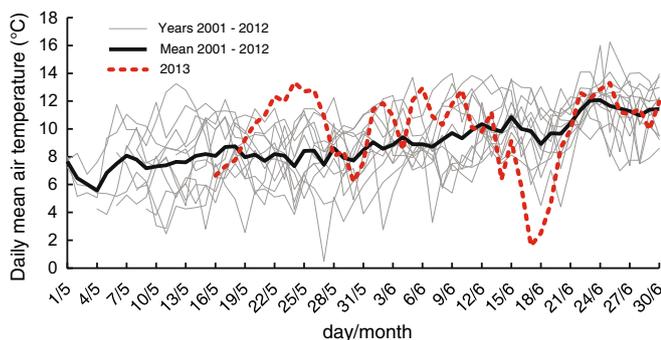


Fig. 6 Daily mean air temperature measured near the snout area of the Gangotri Glacier (3800 m a.s.l., ~20 km north of Kedarnath)

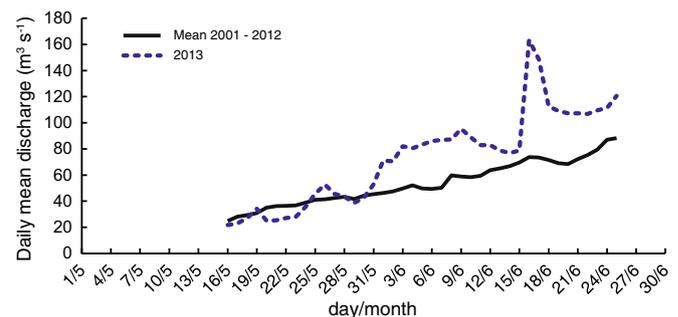


Fig. 7 Daily mean stream discharge measured near the snout area of the Gangotri Glacier (3800 m a.s.l., ~20 km north of Kedarnath)

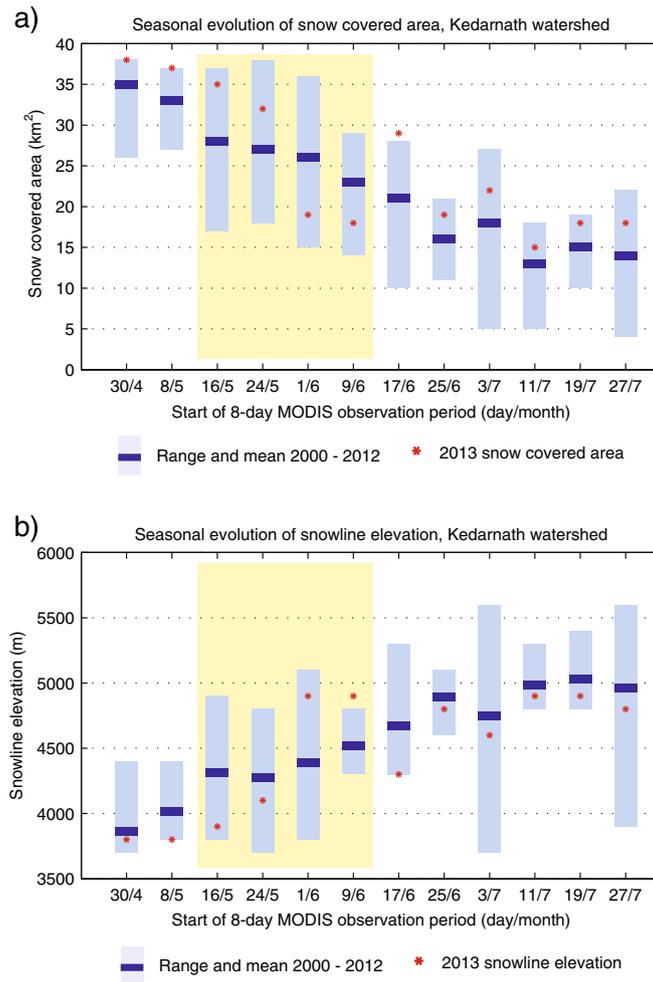


Fig. 8 MODIS derived May to July evolution of a snow-covered area and b snowline elevation for the catchment above Kedarnath village. Values measured during 2013 are compared to the longer term range and mean values for the years 2000–2012. Highlighted (yellow) is the 4-week period preceding the mid-June disaster, during which particularly rapid changes in snow conditions are observed

watershed slope (e.g. Collier and Fox 2003; Costa 1987; Pradeep et al. 2012).

On the basis of all assessed watershed parameters, the situation at Chorabari Lake indicates an anomalous predisposition towards rapid run-off and infilling during enhanced snowmelt or heavy rainfall (Table 2). The lake itself is situated at the second lowest elevation of all lakes in UK and HP. Thus, seasonal thawing of snow will begin earlier in the surrounding watershed, conditions may be more susceptible to unusually warm temperatures, and the onset of monsoon precipitation will deliver a larger proportion of rain rather than snow to the watershed. Melting may be further enhanced by the general south-facing exposition of the watershed. In a glacier-free catchment, rainfall and snowmelt can quickly saturate the ground surface and enter the fluvial drainage system. Drainage density in the ice-free areas of the Chorabari watershed is higher than average but not exceptional (ranked 36 out of 169 lakes), but crucially, steep slopes within the watershed favour fast drainage and concentration of surface flow into a higher order fluvial stream network (mean watershed stream size ranked 7 out of 169 lakes), which drains directly into the lake (as evident in Figs. 1 and 2).

When the assessed individual watershed parameter rankings are combined, Chorabari Lake is identified overall as having the most unfavourable topographic disposition (rank 1, Table 3). In addition, the steep and sharp form of the lateral moraine creates a highly susceptible dam geometry (see Fig. 2a). Other lakes identified with unfavourable topographic dispositional settings encompass a range of different lake and dam forms and many have stable outlet channels. This includes some bedrock dammed lakes, which are not considered susceptible to breaching. Although topographically predisposed lakes are distributed across the states of UP and HP, the likelihood of heavy rainfall triggering events is expected to be greatest where average monsoon rates are highest. In this regard, Chorabari Lake is situated in a zone of high monsoon precipitation relative to most other lakes (8.86 mm day⁻¹ compared to an average of 4.89 mm day⁻¹ across all lakes, Table 3), and in fact, the entire north-eastern corner of UK illustrates a potentially dangerous combination of high monsoon precipitation rates and lakes with unfavourable topographic dispositions (Fig. 10). Several similarly predisposed lakes are located in a notable zone of heavy monsoon precipitation in western HP.

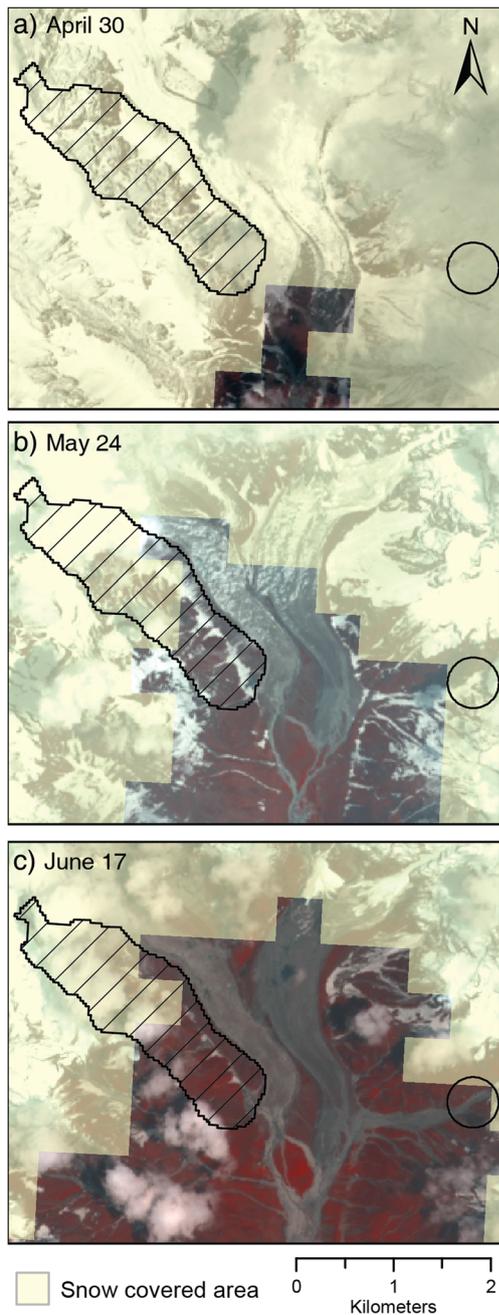


Fig. 9 MODIS-derived snow-covered area in the Kedarnath catchment for the 8-day periods beginning a April 30, b May 24 and c June 17, 2013. Respective Landsat 8 base images are from May 6, May 29 and June 23. *Black outlines* indicate the starting zone of the June 16 debris flow (*circle*), and watershed area of Chorabari Lake (*hatched*)

Discussion

Unseasonably heavy rainfall resulting from the early onset of the monsoon has been well established as the primary cause of widespread landsliding and flooding across the state of UK in mid-June 2013, and previous authors have highlighted the particular susceptibility to such dangers that occurs in regions south of the Himalayan orographic barrier (Dubey et al. 2013). The amount of June rainfall was unprecedented within the 1951–2013 observational record and has been estimated as at least a 100-year event (Singh

et al. 2014). However, snowmelt was also clearly an important factor, and novel integration of MODIS-based snow cover analysis has provided new insight and clarity regarding hydrometeorological triggering of the Kedarnath disaster. Previous studies have suggested that a large increase in snow cover visible in remotely sensed images taken May 21 and post-disaster on June 21 implies that the heavy rain in mid-June would have enhanced melting of an unusually deep snow cover (Durga Rao et al. 2014; Martha et al. 2014; Singh et al. 2014). Our MODIS-based analysis contradicts this interpretation. Despite exceptionally heavy snowfall during winter 2012/2013 (Sati and Gahalaut 2013) and an unusually large snow cover remaining at the beginning of May, snow cover in the Kedarnath watershed was actually well below average when the heavy rainfall arrived in mid-June (Fig. 8). New snowfall would only have been permitted as temperatures cooled towards the very end of the June 15–17 heavy precipitation event. In our view, it is therefore the timing of the early onset of the heavy monsoon rainfall immediately following a prolonged 4-week period of unusually rapid snow cover depletion, rather than the combination of rain falling onto snow-covered ground, that is the crucial hydrometeorological factor in this disaster. It is noteworthy that the June 16 debris flow above Kedarnath was initiated very near the snowline elevation and from a zone within which significant snow loss was visible during the preceding weeks (Fig. 9). MODIS-based snow cover depletion (Fig. 8), visible loss of snow within the Chorabari Lake watershed area (Fig. 9) and discharge data from a nearby watershed (Fig. 7), all suggest an unusually large snowmelt contribution to the lake volume prior to the onset of the heavy rainfall and catastrophic breaching on June 17.

The unusual situation of the Chorabari Lake being dammed in a steep, unstable paraglacial environment but fed entirely from a fluvial catchment has been recognized as particularly important in the context of the Kedarnath disaster. Heavy rain falling onto a glaciated catchment will be delayed in its movement from the glacier surface, through the firn and into the subglacial and englacial drainage network. This is particularly true in spring because (1) water storage in the firn layer delays run-off, (2) crevasses which serve as the most direct conduit of water from the glacier surface are still partially snow filled and (3) the network of surface, subglacial and englacial channels are not yet fully developed and connected (Fountain and Walder 1998). Thus, there is a buffering effect and heavy rainfall over several days, particularly in spring or early summer, may be unlikely to lead directly to catastrophic accumulation in a typical glacier-fed moraine dammed lake. At Kedarnath, where the ground was already saturated and streams running high from snowmelt, the unseasonably heavy rainfall drained rapidly from the steep, glacier-free slopes and quickly overwhelmed the relatively small capacity of Chorabari Lake. Had a stable outlet channel existed, the snowmelt component within the lake would most likely have drained prior to the onset of the heavy rainfall in mid-June, avoiding critical water volumes accumulating in the lake.

In the Himalaya, large-scale GLOF hazard assessment schemes have not previously considered parameters relevant to potential hydrometeorological triggering, and emphasis has rather been given to potential impacts from rock and ice falls or avalanches (e.g. ICIMOD 2011; Worni et al. 2013). The Kedarnath disaster should serve to reiterate the potential importance of hydrometeorological triggering of lake outburst flooding, and hazard

Table 2 Topographical parameters calculated for 169 glacial lakes across the Indian Himalayan states of Uttarakhand and Himachal Pradesh

Assessed watershed (WS) parameters	Relevance	Median all lakes [range]	Chorabari value	Chorabari rank
Lake elevation	Lower elevation increases likelihood of rainfall and snowmelt within the lake watershed.	4830 m [3750–5670]	3850 m	2
Nonglacial watershed component (WS_{ng}) ($WS_{ice-free}$, WS_{dir})	Glaciers provide a buffering effect during high and low run-off events. More immediate response to rain and snowmelt is expected in an ice-free watershed where fluvial drainage dominates.	0.24 [0.00–10.73]	2.27	13
Mean stream size ^a (<i>Strahler number</i>)	Large waterways increase the capacity of the watershed to transport run-off from snowmelt and rainfall to the lake.	1.21 [0.00–1.91]	1.76	7
Drainage density ^a (<i>Stream length/WS_{ice-free}</i>)	High drainage density increases the capacity of a watershed to transport run-off from snowmelt and rainfall to the lake.	1.57 km km ⁻² [0.00–6.27]	2.3 km km ⁻²	36
Mean slope ^a	High relief and steep-sided watersheds favour faster run-off and flow concentration within streams.	26° [6–42]	35°	9

For each parameter, lakes are comparatively ranked. Low-ranking values indicate greater predisposition towards overflow and catastrophic breaching from snowmelt and rainfall run-off

^a Only ice-free areas of the watershed are included in this calculation.

assessment schemes should be adjusted accordingly to consider a fuller range of triggering factors. The concept of watershed area (Huggel et al. 2002; McKillop and Clague 2007) clearly does not on its own sufficiently identify the potential susceptibility of such

Table 3 Final ranking of topographic disposition, based on the sum of individual parameters ranked in Table 2

Rank	Location	Lake and dam type	Stable outlet channel	Average daily monsoon precipitation	Dam geometry (susceptibility) ^a	Steep sediment abundance ^b
1	79° 3' 40" E 30° 44' 51" N	Lateral moraine dammed lake (with ice)	No	8.86 mm	High	Yes
2	79° 37' 6" E 30° 41' 54" N	Cirque lake, bedrock dam	No	7.30 mm	Very low	Yes
3	77° 47' 20" E 31° 50' 57" N	End-moraine dammed lake	Yes	5.36 mm	Moderate	No
4	78° 4' 55" E 32° 25' 21" N	Partially glacial melt-fed lake dammed by outwash gravel and debris	No	5.36 mm	Low	Yes
5	80° 39' 9" E 30° 21' 17" N	End-moraine dammed lake	Yes	7.47 mm	High	Yes
6	76° 18' 56" E 32° 20' 33" N	Glacier erosion lake, bedrock dam ^c	Yes	10.00 mm	Very low	Yes
7	76° 56' 57" E 32° 46' 36" N	Lateral moraine dammed lake (complex)	Yes	4.15 mm	Moderate	Yes
8	77° 13' 10" E 32° 31' 31" N	End-moraine dammed lake	Yes	3.83 mm	High	Yes
9	80° 30' 40" E 30° 24' 28" N	End-moraine dammed lake	No	7.47 mm	High	Yes
10	77° 32' 47" E 32° 29' 54" N	End-moraine dammed lake	Yes	3.38 mm	Low	No
Average across all 169 lakes				4.89 mm		

The 10 lakes with the most unfavourable topographic disposition are listed (out of 169 lakes). Average monsoon precipitation (June–July–August) is from TRMM, for the period 1998–2012 (see also Fig. 10)

^a The qualitative assessment of moraine dam geometry outburst susceptibility encompasses (1) Moraine dam width-to-height ratio, (2) width of crest of moraine dam and (3) slope of downstream face of moraine dam, based on the criteria outlined in Worni et al. (2013). Herein, high/moderate/low susceptibility is assigned where respectively >2, 1 or none of these individual components show critical values, based on inspection of Google Earth imagery. Bedrock dams are assigned very low susceptibility

^b Qualitative assessment based on the identification of steep, loose, nonvegetated sediment within the area immediately downslope of the lake (~2000 m zone)

^c Part of a sequence of four lakes, formed in glacially eroded depressions

June-July-August average precipitation (1998 – 2012)

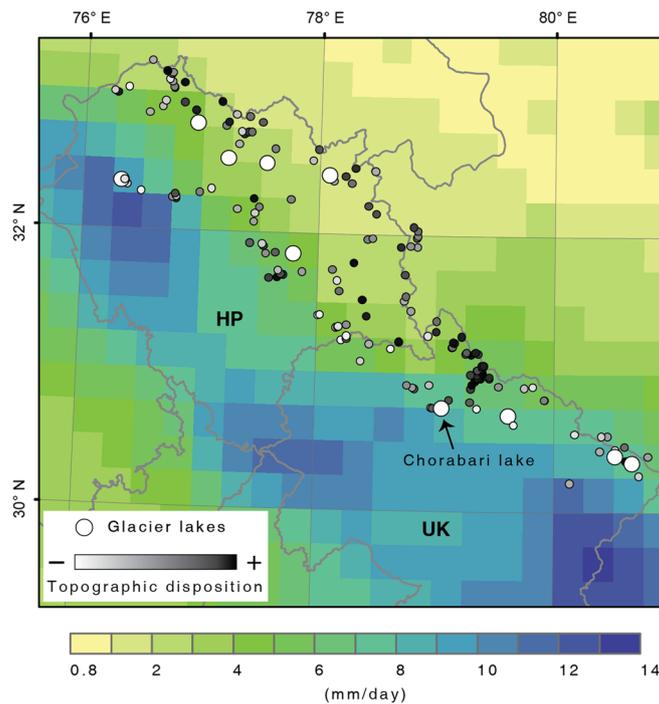


Fig. 10 TRMM average daily precipitation over the states of Uttarakhand (UK) and Himachal Pradesh (HP) for the monsoon months of June, July and August (1998–2012), overlaid with the results of the glacial lake topographic disposition assessment. *Light colours* indicate a low ranking and greater predisposition towards catastrophic breaching from snowmelt and rainfall run-off. The 10 lakes with the most unfavourable topographic disposition are indicated with enlarged symbols (see also Tables 2 and 3)

situations, where it is not the absolute size of the watershed that is anomalous, but rather the drainage characteristics. The assessment of topographic disposition applied herein is simple and easily established over large datasets but clearly identified the unique susceptibility of Chorabari Lake within a sample of 169 glacial lakes. Successful application of this concept to other known snowmelt and rainfall-triggered GLOFs, and particularly across other high mountain regions, will enable refinement and potentially weighting of the most important topographic parameters. Where topographically predisposed glacial lakes are located in areas of high precipitation, further local-scale investigations of dam structure and recognition of downstream threats are recommended. The Kedarnath disaster has illustrated that the greatest threats occur or could yet evolve at lowest elevations, where snowlines retreat fastest, monsoon precipitation can predominate as rainfall and fluvial run-off may prevail in largely ice-free watershed areas. The paradox is that it is exactly these same locations where risks are most exacerbated by villages and infrastructure, as poorly regulated development expands at unprecedented rates high into vulnerable Himalayan valleys (Chand 2014; Sati and Gahalaut 2013; Uniyal 2013).

Inevitably, questions have been raised concerning the role of climate change in the Kedarnath disaster and future potential threats. In principle, it is very difficult to link any individual extreme hydrometeorological event to changes in the climate system (Bindoff et al. 2013; Seneviratne et al. 2012). However, an increase in heavy rainfall events associated with the Indian monsoon has been observed over the past 50 years (Christensen et al. 2013), and there is some evidence that anthropogenic influence on

the climate system had increased the probability of occurrence of the June 2013 rainfall event in Northern India (Singh et al. 2014). While changes in monsoon timing and seasonal snow cover are uncertain, an increasing number of studies have reported on glacier ice loss across the Himalaya (Bolch et al. 2012; Kääb et al. 2012) and the attribution of this loss to anthropogenic causes (Marzeion et al. 2014). More specifically relating to the breaching of Chorabari Lake, Dobhal et al. (2013b) have reported an average of 15 m vertical loss of ice over the lower region of the glacier from 2003 to 2010 alone, and up to 0.072 km² of loose, steep moraine has been exposed since 1962. This sustained downwasting and retreat, be it driven by natural or anthropogenic climate forcing, has undoubtedly increased the height and steepness of the lake dam, thereby reducing dam stability, and has increased the debris flow threat above Kedarnath over time.

The potentially catastrophic combination of heavy early monsoon rainfall coinciding with spring snowmelt and high stream flows could be expected with increased frequency in the 21st century, with both an earlier onset of the South Asian monsoon and more extreme associated precipitation projected (Christensen et al. 2013). As the overall glacier-covered area further reduces (Bolch et al. 2012), catchments in the Himalaya will increasingly become rainfall dominated (Collins et al. 2013; Immerzeel et al. 2012), with the buffering effect of glaciers during both extremely high and low rainfall periods diminishing. At the same time, new lakes will form, and steep, loose, poorly consolidated sediment stores will continue to be exposed and enhanced in former glaciated areas. Hence, the Kedarnath disaster could be considered as a prelude to the type of impacts that can be expected with increased frequency over the 21st century in the Himalayan states.

Conclusions

The lake outburst and debris flow disaster originating above Kedarnath resulted from an amalgamation of unusual hydrometeorological conditions, an unfavourable topographical disposition of the lake and watershed area, an unstable dam structure and lack of any stable lake outlet channel. The timing of the unseasonably heavy rainfall in mid-June was critical, following a 4-week period of unusually rapid snow cover depletion and elevated streamflow in the watershed above Kedarnath, which, in turn, was likely initiated by very warm temperatures beginning in mid-May. Slopes around Kedarnath were saturated, and the topographic characteristics of the Chorabari Lake watershed favoured fast and ultimately catastrophic drainage of rainfall and snowmelt run-off into the lake.

The integration of MODIS-based snow cover mapping has allowed a first, systematic assessment of the hydrometeorological conditions leading to the Kedarnath disaster, enhanced with nearby temperature and run-off data. While TRMM-based analyses are well established in landslide and flood applications, MODIS offers great potential in near real-time monitoring of snow cover characteristics in remote mountain regions. Particularly in topographically predisposed lake catchments and in the absence of discharge monitoring, snow cover depletion mapped with MODIS could provide an early indication warning where streamflows and lake levels could be critical, prior to the onset of forecasted heavy rainfall.

Often, the GLOF threat in high mountain regions is manifested in the form of rapidly expanding lakes, precariously situated beneath steep ice or rock walls. The Kedarnath disaster should serve as a reminder that some threats are less overt, but equally pronounced, and the broader consideration of lake watershed characteristics introduced here should complement any comprehensive large-scale approach to GLOF hazard assessment. Furthermore, the potential for Kedarnath-type hydrometeorological lake breaching is expected to increase as glaciers recede or ultimately disappear, and watersheds become increasingly rainfall dominated. Hence, a long-term perspective to GLOF hazard assessment and management is required, as the greatest threat may only be realized in an ice-free environment. Understanding gained from the Kedarnath disaster should therefore guide further hazard and risk studies accordingly.

Acknowledgments

Landsat images and MODIS data were acquired through the USGS Earth Explorer and NASA Reverb portals, respectively. TRMM data were extracted from the NASA Giovanni portal. Post-disaster photographs were kindly provided by Daniel Grossman. The authors acknowledge the financial support from the Indian Himalayas Climate Adaptation Programme (IHCAP; www.ihcap.in) of the Swiss Agency for Development and Cooperation (SDC).

References

Arora M, Kumar R, Singh RD, Malhotra J, Kumar N (2014) Analysis of unusual meteorological conditions that led to recent floods in Bhagirathi Basin (Uttarakhand Himalayas). *Hydrol Sci J*. doi:10.1080/02626667.2014.951362

ASTER GDEM Validation Team (2011) ASTER Global Digital Elevation Model Version 2—summary of validation results. NASA Land Processes Distributed Active Archive Center and the Joint Japan-US ASTER Science Team

Bajracharya S, Shrestha F, Bajracharya S, Maharjan S, Guo W (2014) GLIMS Glacier Database. Boulder, CO. National Snow and Ice Data Center. doi: 10.7265/N5V98602

Bindoff NL, Stott PA, AchutaRao KM et al (2013) Detection and attribution of climate change: from global to regional. In: Stocker TF et al (eds) *Climate change 2013: the physical science basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 867–952

Bolch T, Kulkarni A, Kaab A et al (2012) The state and fate of Himalayan glaciers. *Science* 336:310–314

Chand R (2014) Himalayan tsunami: disaster natural but damage man-made. *Int J Multidiscip Approach Stud* 1:51–64

Christensen JH, Krishna Kumar K, Aldrian E et al (2013) Climate phenomena and their relevance for future regional climate change. In: Stocker TF et al (eds) *Climate change 2013: the physical science basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1217–1308

Clague JJ, Evans SG (2000) A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quat Sci Rev* 19:1763–1783

Collier C, Fox NJ (2003) Assessing the flooding susceptibility of river catchments to extreme rainfall in the United Kingdom. *Int J River Basin Manag* 1:1–11

Collins D, Davenport JL, Stoffel M (2013) Climatic variation and runoff from partially-glacierised Himalayan headwater basins of the Ganges. *Sci Total Environ* 468–469:s48–s59

Costa JE (1987) Hydraulics and basin morphometry of the largest flash floods in the conterminous United States. *J Hydrol* 93:313–338

Das S, Kar NS, Bandyopadhyay S (2015) Glacial lake outburst flood at Kedarnath, Indian Himalaya: a study using digital elevation models and satellite images. *Nat Hazards*. doi:10.1007/s11069-015-1629-6

Dobhal DP, Gupta AK, Mehta M, Khandelwal DD (2013a) Kedarnath disaster: facts and plausible causes. *Curr Sci* 105:171–174

Dobhal DP, Mehta M, Srivastava D (2013b) Influence of debris cover on terminus retreat and mass change of Chorabari Glacier, Garwal region, central Himalaya, India. *J Glaciology* 59:961–971

Dubey CS, Shukla DP, Ningreihon AS, Usham AL (2013) Orographic control of the Kedarnath disaster. *Curr Sci* 105:1474–1476

Durga Rao KHV, Venkateshwar Rao V, Dadhwal VK, Diwakar PG (2014) Kedarnath flash floods: a hydrological and hydraulic simulation study. *Curr Sci* 106:598–603

Fountain AG, Walder JS (1998) Water flow through temperate glaciers. *Rev Geophys* 36:299–328

Frey H, Paul F, Strozzini T (2012) Compilation of a glacier inventory for the western Himalayas from satellite data: methods, challenges, and results. *Remote Sens Environ* 124:832–843

Fujita K, Sakai A, Takenaka S, Nuimura T, Surazakov AB, Sawagaki T, Yamanokuchi T (2013) Potential flood volume of Himalayan glacial lakes. *Nat Hazards Earth Syst Sci* 13:1827–1839

Gruber S (2012) Derivation and analysis of a high-resolution estimate of global permafrost zonation. *Cryosphere* 6:221–233

Guha-Sapir D, Below R, Hoyois P (2014) EM-DAT: International Disaster Database. Université Catholique de Louvain, Brussels, Belgium. www.emdat.be. Accessed 20 Nov 2014

Hall DK, Riggs GA, Salomonson VV, DeGirolo NE, Bayr KJ, Jin JM (2002) MODIS snow-cover products. *Remote Sens Environ* 83:181–194

Hasson S, Lucarini V, Khan MR, Petitta M, Bolch T, Giori G (2014) Early 21st century snow cover state over the western river basins of the Indus River system. *Hydrol Earth Syst Sci* 18:4077–4100

Huggel C, Kääb A, Haeblerli W, Teysseire P, Paul F (2002) Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. *Can Geotech J* 39:316–330

ICIMOD (2011) Glacial lakes and glacial lake outburst floods in Nepal. International Centre for Integrated Mountain Development (ICIMOD), Kathmandu

IMD (2013) A preliminary report on heavy rainfall over Uttarakhand during 16–18 June 2013. India Meteorological Department (IMD), Ministry of Earth Sciences, Government of India

Immerzeel WW, Droogers P, de Jong SM, Bierkens MFP (2009) Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. *Remote Sens Environ* 113:40–49

Immerzeel WW, van Beek LPH, Konz M, Shrestha AB, Bierkens MFP (2012) Hydrological response to climate change in a glacierized catchment in the Himalayas. *Climate Change* 110:721–736

Joseph S, Sahai AK, Sharmila S et al (2014) North Indian heavy rainfall event during June 2013: diagnostics and extended range prediction. *Clim Dyn*. doi:10.1007/s00382-014-2291-5

- Kääb A, Berthier E, Nuth C, Gardelle J, Arnaud Y (2012) Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature* 488:495–498
- Korup O (2004) Geomorphometric characteristics of New Zealand landslide dams. *Eng Geol* 73:13–35
- Martha TR, Roy P, Govindharaj KB, Kumar KV, Diwakar PG, Dadhwal VK (2014) Landslides triggered by the June 2013 extreme rainfall event in parts of Uttarakhand state. *India Landslides*. doi:10.1007/s10346-014-0540-7
- Marzeion B, Cogley JG, Richter K, Parkes D (2014) Attribution of global glacier mass loss to anthropogenic and natural causes. *Science* 345:919–921
- Mathew J, Giri Babu D, Kundu S, Vinod Kumar K, Pant CC (2014) Integrating intensity–duration-based rainfall threshold and antecedent rainfall-based probability estimate towards generating early warning for rainfall-induced landslides in parts of the Garhwal Himalaya, India. *Landslides* 11:575–588
- McKillop RJ, Clague JJ (2007) Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia. *Glob Planet Chang* 56:153–171
- Mehta M, Majeed Z, Dobhal DP, Srivastava P (2012) Geomorphological evidences of post-LGM glacial advancements in the Himalaya: a study from Chorabari Glacier, Garhwal Himalaya, India. *J Earth Syst Sci* 121:149–163
- Nadim F, Kjekstad O, Peduzzi P, Herold C, Jaedicke C (2006) Global landslide and avalanche hotspots. *Landslides* 3:159–173
- O'Connor JE, Hardison JH, Costa JE (2001) Debris flows from failures of Neoglacial-Age moraine dams in the Three Sisters and Mount Jefferson wilderness areas, Oregon. *US Geological Survey Professional Paper* 1606
- Petley D (2013) Reconstructing the events at Kedarnath using data, images and eyewitness reports. *The Landslide Blog*, 4 July 2013. <http://blogs.agu.org/landslideblog/>. Accessed 20 Nov 2014
- Pradeep PK, Pant CC, Tiwari PC, Pant PD, Sharma AK (2012) Spatial variability assessment of riverline floods and flash floods in Himalaya. *Disaster Prev Manag: Int J* 21:135–159
- Richardson SD, Reynolds JM (2000) An overview of glacial hazards in the Himalayas. *Quat Int* 65(66):31–47
- Sati SP, Gahalaut VK (2013) The fury of the floods in the north-west Himalayan region: the Kedarnath tragedy. *Geomatics, Nat Hazards Risk* 4:193–201
- Seneviratne SJ, Nicholls N, Easterling et al (2012) Changes in climate extremes and their impacts on the natural physical environment. In: Field CB (ed) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp 109–230
- Sengupta R (2013) In Uttarakhand, a pilgrimage of horrors. *Live Mint*, 1 July 2013. www.livemint.com/Politics/JvCO1EbT7O7QfSV7BVUtPM/In-Uttarakhand-a-pilgrimage-of-horrors.html. Accessed 20 Nov 2014
- Singh D, Horton DE, Tsiang M et al. (2014) Severe precipitation in Northern India in June 2013: causes, historical context, and changes in probability. In: Herring SC, Hoerling MP, Peterson TC, Stott PA (eds) *Explaining extreme events of 2013 from a climate perspective*. Bulletin of the American Meteorological Society Vol. 95, No. 9, September 2014. American Meteorological Society
- Uniyal A (2013) Lessons from Kedarnath tragedy of Uttarakhand Himalaya, India. *Curr Sci* 105:1472–1473
- Valdiya KS, Paul SK, Chandra T, Bhakuni SS, Upadhyaya RC (1999) Tectonic and lithological characterization of Himadri (Great Himalayan) between Kali and Yamuna Rivers, central Himalaya. *Himal Geol* 20:1–17
- Vilimek V, Emmer A, Huggel C, Schaub Y, Würmli S (2013) Database of glacial lake outburst floods (GLOFs)—IPL project No. 179. *Landslides* 11:161–165
- Worni R, Stoffel M, Huggel C, Volz C, Casteller A, Luckman B (2012) Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina). *J Hydrol* 444–445:134–145
- Worni R, Huggel C, Stoffel M (2013) Glacier lakes in the Indian Himalayas—from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes. *Sci Total Environ* 468–469:571–584

S. K. Allen · P. Rastner · C. Huggel

Department of Geography,
University of Zurich,
Zurich, Switzerland

S. K. Allen (✉) · **M. Stoffel**

Institute for Environmental Sciences,
University of Geneva Switzerland,
Geneva, Switzerland
e-mail: simon.allen@geo.uzh.ch

P. Rastner

EURAC-Institute for Applied Remote Sensing,
Bolzano, Italy

M. Arora

National Institute of Hydrology,
Roorkee, Uttarakhand, India

M. Stoffel

Dendrolab.ch, Institute of Geological Sciences,
University of Berne,
Bern, Switzerland