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Terrain response to the extreme rainfall event of June 2013: Evidence from the Alaknanda and Mandakini River Valleys, Garhwal Himalaya, India

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The present study is based on the field observations and geochemical analyses of flood sediments to ascertain the nature and causes of destruction in the Mandakini and Alaknanda river valleys during June 2013. The study suggests that the sediments were contributed from two major sources: the moraines and alluvial fans located in the Trans and Higher Himalaya; and the landslides in the Higher and Lesser Himalaya. Although the flood was the result of a high intensity rainfall event, the magnitude was increased due to the proliferation of settlements along the river and a series of partially constructed barrages on the river bed. Geochemical analyses of the flood sediments indicated that the contribution of power-project generated debris locally enhanced the flood magnitude. Further, the study argues that the terrain north of the Main Central Thrust (Higher Himalaya) should be kept free from major interventions, including hydropower projects, to reduce flood hazards. The study finally calls for a critical re-evaluation of current development policy and the approach towards harnessing the enormous hydropower potential of the Himalayan rivers in general and in the Uttarakhand Himalaya in particular.

Background

The June 2013 flash flood in the Mandakini and Alaknanda river valleys has been widely debated and discussed in many scientific publications (Sati and Gahalaut, 2013; Dobhal et al., 2013; Rana et al., 2013; Mishra and Srinivasan, 2013; Rao et al., 2014; Singh, 2014). These papers provide detailed scientific analyses of the hydro-

meteorological conditions that prevailed during 15th to 18th June 2013, flood magnitude, downstream impact and suggestions for safeguarding the area from similar calamities in the future. Since the majority of the published studies focused on the role of Chorabari Lake, and the damage caused around Kedarnath valley, with brief remarks on the Mandakini valley, many critical scientific questions pertaining to this flood remain unaddressed. The present study therefore, makes an attempt to provide answers to the questions like (i) the genesis of the June 2013 flood in the Mandakini and the Alaknanda valleys; (ii) sediment scavenging and downstream transportation mechanisms; (iii) flood impact due to infrastructure development along the river bed (e.g. buildings and hydro projects); and finally, and most importantly, (iv) quantification of the debris generated by hydropower projects (if any) and its role in bulking the river flow.

Flash floods in the study area are usually caused by high intensity focused rainfall on the face of an orographic barrier, particularly in river valleys that are located to the south of the tectonically active Main Central Thrust (MCT) (Fig. 1) where the hill slopes are near the threshold for land sliding. Landslides caused by increased pore water pressure on steep slopes to the south of the MCT led to the obstruction of stream courses (Rana et al., 2013), and breaching of these obstructions results in a highly peaked flood carrying voluminous amounts of sediment downstream (cf. Carling, 2013).

During the last 200 years two major flash floods occurred in the Alaknanda valley that are reasonably well documented. On 6th September 1893, a tributary of the Alaknanda river called the Birehi Ganga was blocked by ~ 5000 million tons of rock which fell from a 900 m high valley flank. The debris formed a lake 270 m deep, 3 km long at the base and 600 m wide at the summit (Holland, 1984; Pal, 1986; Fig. 2a). This lake was known as the Ghona lake. On 25th August 1894 at midnight the dam partly collapsed, sending flood surges downstream. The flood lasted until the morning of 26th August causing unprecedented damage to property in Srinagar town; but there was no loss of life reported.

Seventy six years later, in July 1970, the Alaknanda valley witnessed another major flood. This was ascribed to a cloudburst on

Figure 1. DEM of Uttarakhand Himalaya. MFT-Main Frontal Thrust, MBT-Main Boundary Thrust, MCT-Main Central Thrust, STDS-South Tibetan Detachment System. BR-Bhilangna river, MR-Mandakini river, AR- Alaknanda river, NR-Nayar river, DG-Dhauliganga river, PR-Pinder river. MCT is a zone of recurrent seismicity as indicated by the concentration of earthquake epicenters (source: <http://earthquake.usgs.gov/earthquakes/eqarchives/epic/>) and physiographic boundary between Lesser and Higher Himalaya.

the night of July 20th 1970 in the zone of the MCT and transported around 15.9×10^6 tons of sediment (Kumar and Shone, 1970) and filled the 1894 Gohna Lake to its brim (Fig. 2a). This flood caused large-scale destruction in the lower reaches including destruction of the lower Srinagar town and clogging of the upper Ganga canal at Haridwar.

The cause of the 1970 flood was widely debated in the country. A section of scientists were of the opinion that the flood was independent of deforestation. But a small group of scientists and local inhabitants believed that the flood had its genesis to the large-scale commercial forest felling in the preceding years (for key references see Wasson et al., 2008).

Beyond the historical records, flood histories can be reconstructed using the flood sediment archives, notably slack water deposits (Kale 2007; Baker, 2008). In the high-energy fluvial environment of the Himalaya, the preservation of slack water deposits is rare. Therefore, ascertaining flood frequencies beyond the historical record is very difficult. However, some progress towards locating and analyzing the record of past flood sediments in the Alaknanda valley has been made (e.g. Srivastava et al., 2008; Wasson et al., 2008; 2013). These studies suggest that during the last 1000 years, major floods were caused by natural landslide dam bursts in the upper Alaknanda catchment and that the 1970 flood was the highest in magnitude so far (Wasson et al., 2008). But in a more recent study it was speculated

that the June 17th 2013, flood surpassed all the record of last 1000 year floods in the region (Wasson et al., 2013). However that was contested by Rana et al. (2013).

Mandakini Valley

The Mandakini river originates from Chorabari Lake and its companion glaciers at 3840 m altitude and is joined by the Son Ganga, Kali Ganga and Madhyamaheshwar Ganga before it meets the Alaknanda river at Rudraprayag at 600 m altitude (Fig. 3). The MCT is the major structure that constitutes a wide zone between Kund (southeast of Guptkashi) and Rambara (located below Kedarnath) (Valdiya 2014 and references therein). The zone of the MCT consists of highly sheared and pulverized rocks. The majority of the active and stabilized landslides can be found above Kund village and below Gaurikund villages (Fig. 3). Some prominent landslides are at Bhenti-Burua and Kunjethi in tributary valleys and the serious Byung landslide on the way to Sonprayag along the Mandakini river (Chaudhary et al., 2010). These landslides are a major source of sediments to the Mandakini river. Geomorphologically, the Mandakini valley can be divided into three broad zones. These from northwest to southeast: the upper glaciated zone (A) (>3500 m) located above Kedarnath valley; the middle paraglacial zone (B) located between Kedarnath and Gaurikund (<3500 m to 2000 m);

Figure 2. (a) 1894 picture of Gohna Lake formed due to the blocking of the Birehi Ganga by a massive landslide seen as a light colored triangular scar on the far right of the picture. (b) Gohna Lake after the 1970 flood (Source: http://www.the-south-asian.com/April-June2008/Gohna_Lake.htm).

and the lower fluvial zone (C) (<2000 m) below Sitapur (Fig. 3). The longitudinal river profile shows three major discontinuities located around Kedarnath, Rambara and Sitapur villages respectively and, below these breaks, the river follows a graded course (Fig. 4).

During 15th to 18th June 2013, high intensity rainfall engulfed most of Uttarakhand. The meteorological station of the WIHG located at an elevation of 3820 m in the Mandakini river valley recorded 325 mm rainfall during 15th and 16th June 2013. According to Dobhal et al. (2013), the rainfall created significant terrain instability by mobilizing unconsolidated moraines and alluvial fan deposits around the Kedarnath valley. It is argued that the Chorabari Lake not only devastated Kedarnath town, but was responsible for destruction in the lower reaches of the Mandakini river. Using differential GPS (Lieca make CS-10 model) in Real Time Kinematic mode, the relict lake boundary was mapped. Using the strand line mark (<5 m and its maximum extent) it is estimated that the lake had an area of ~41000 m² (Fig. 5a, b and c) and held ~0.2 million cubic meters of water before being breached. The steep gradient streams (270 m/km) with a high steepness index (k_s) of 447 around Kedarnath together with the sudden surge of water from the breached lake caused unprecedented devastation in the Kedarnath valley. The steepness index is a proxy of stream power that in most cases is directly proportional to its capability for vertical and lateral erosion (Kirby et

al., 2003; Tyagi et al., 2009). Therefore, the zones with highest steepness index under even normal flood conditions are vulnerable to erosion. Further downstream (between Kedarnath and Gaurikund), although the river gradient decreases to 138 m/km, the severity of lateral erosion and incision remained unabated and the k_s decreases marginally to 424.

The Kedarnath valley has undergone multiple phases of glaciations. A recent study by Mehta et al., (2012) has shown that there were four glacial expansions between 13 ka and 5 ka represented by the trail of moraines. Further, in recent times, the area vacated by the glaciers (Bhambri et al., 2011) has left behind appreciable amounts of glaciogenic sediments implying that valley is not sediment limited. Thus, presence of streams with high gradient and high k_s coupled with high intensity rain and a lake outburst provided ideal geomorphic circumstances for mobilization of the unconsolidated moraines in the form of debris flows. Such high sediment-water ratio (debris flows) are capable of scavenging the riverbed and valley flank sediments (Montgomery et al., 2004). A very conservative estimate suggests that >0.35 million cubic meters of sediment (dominated by glaciogenic material) was transported from the upper glacial and middle paraglacial domains and a major volume of the sediment was trapped at Sonprayag and Sitapur villages where the river gradient and k_s drops significantly (23 m/km and 195 respectively). At these locations the riverbed level was at 1611 m before the flood and rose to 1640 m after the flood implying ~29 m rising of the riverbed due to sediment aggradation. Pre- and post-flood pictures also substantiate this observation (Fig. 6a and b).

Below Sitapur village and above the confluence of the Kali and Madhyamaheshwar Ganga tributaries, there is an appreciable decrease

Figure 3. Drainage map of the Mandakini Valley (A) upper glaciated terrain, (B) middle paraglacial terrain and (C) the lower fluvial terrain. Black rectangular boxes are the location of flood sediment samples collected for geochemical analyses.

Figure 4. Longitudinal profile of the Mandakini river showing distinct breaks around Kedarnath, Rambara and Sonprayag-Sitapur (inset: section enlarged between Kedarnath and Sitapur). These discontinuities acted as depocenters for the sediments transported down valley from Kedarnath.

Figure 5. (a) Drainage map of the Kedarnath valley showing the glaciers and streams. The position of Chorabari Lake is also marked. (b) Chorabari Lake mapped in the month of October 2013 using differential GPS in Real Time Kinematic mode. (c) Relict Chorabari Lake (facing west); picture taken in October 2013.

in the flood sediments. However, a thick sediment pile on the Mandakini river bed reappears below the confluence and continues until the Mandakini and Alaknanda confluence at Rudraprayag town (Fig. 3). One of the reasons for such a high sediment contribution is because the catchments of these rivers contain extensive old landslide deposits that were generated during the 1999 cloud burst (Kimothi et al., 1999; Rautela and Thakur, 1999; Sati et al. 2002). Additionally, the terrain in the vicinity of the MCT is undergoing accelerated erosion which is ascribed to seismicity and monsoon rainfall focused on the MCT zone (Vance et al., 2001; Vaidyanathan et al 2002; Wobus et al., 2005). During the present field investigations ~60 new landslides were mapped in the Mandakini, Kali and Madhyamaheswar Ganga valleys. These landslides were generated by toe erosion and are not buffered by terraces and/or flood plains.

Downstream, near Kund village, the partially constructed 22 m high Singoli-Bhatwari barrage did not suffer major structural damage, but the 30 m high right flank of the valley was scoured during the flood (Fig. 3). Owing to this, a temporary lake was created behind the barrage bays and the backwater extended below Semi village. This village is located over a surface with a curvilinear scarp of crystalline rocks and subsidence is reported by villagers. It is not clear, however, how long the lake persisted during the June 2013 flood or also how far upstream the lake had extended. The evidence such as, the sediment piles, river bank scars caused due by toe erosion and partial erosion of the debris that were piled up along the right bank (below Semi village) indicate that the lake possibly extended below the village. It is likely that following breaching of the lake, drawdown could be one of the reasons for the reported subsidence around Semi village.

The Mandakini river valley widens after crossing the MCT at Kund village. The topography becomes less rugged, river gradient drops significantly (6 m/km) and the k_s value decreases to 77. There is a different pattern of damage caused by the river between Kund to Tilwara. Close scrutiny of the damage indicates that below the proposed Singoli-Bhatwari power house, which is located a few kilometers upstream of Vijaynagar town, the river seems to have migrated laterally (within the confines of the valley) causing erosion of the non-cohesive river banks. Any structures built on such banks had either collapsed or were engulfed in the torrent of floodwater. One of the sites of worst damage was at the Chandrapuri tourist resort.

Based on the nature of preserved sediments such as a patchy occurrence of poorly organized lithoclasts in a sand matrix above Sitapur and crudely laminated lithoclasts imbedded in sandy matrix between Vijaynagar, Agastmuni and Tilwara suggests that the debris flow dominated until reaching Sitapur village.

Figure 6. Field photographs of Sitapur that acted as the last major trap for the sediments transported from the Kedarnath valley and its tributary valleys. (a) Picture taken immediately before the flood (on 15th June) one can see five hairpin bends above the riverbed. (b) After the flood (July 2013) only three hairpin bends are visible which shows the magnitude of sediment trapped at this location. The pre- and post- riverbed elevations indicate that a ~29 m thick sediment pile is accommodated at Sitapur.

Following that, a combination of debris and hyperconcentrated flow took place. Studies have shown that under an hyperconcentrated flow regime, rivers tend to (i) aggrade in areas where velocity drops (wide valley expanses/ meanders) and (ii) migrate laterally in order to follow the minimum resistance path (Jakob and Hungr, 2005). We ascribe the destruction due to the lateral erosion of the unconsolidated river bank sediment (terraces and old debris flows) to the hyperconcentrated flow of the Mandakini river at Vijaynagar, Agastmuni and Tilwara towns respectively (Fig. 3 and 7).

Alaknanda valley

In the Alaknanda valley, flood damage was largely confined to two locations: between Lambagarh and Govindghat villages in the Higher Himalaya proximal to the Pindari Thrust; and around Srinagar town in the Lesser Himalaya proximal to the North Almora Thrust (Fig. 8). Unlike the Mandakini valley, there was no lake outburst; instead the flood was solely due to torrential rain that occurred during the same periods (15th to 17th June 2013).

Around Vishnuprayag: There is no meteorological record at the

Vishnuprayag hydropower project site. However, at Joshimath (~30 km south of the project site) 265 mm rainfall fell during 15–17 June, with a maximum of 114 mm rainfall occurring in 24 hrs ending on June 17th. In the early morning of 16th June, the flood record showed a discharge of 155 cumec which increased to ~2000 cumec on the June 17 and blocked 3 bays with large boulders and other sediments (according to the project officials the suspended sediment load on 16th morning was >2000 ppm). The 8.5 m radial gates were not designed to allow huge boulders to bypass, therefore obstructions caused by the boulders and uprooted trees impounded the floodwater behind the barrage. The major flood pulse arrived at the barrage site on 17th June and scoured a 50 m wide part of an old landslide deposit on the left flank washing away site offices, a helipad, and a large stretch of the national highway, and transported large amount of boulders downstream (*Source: Expert committee report on “Assessment of Environmental Degradation and Impact of Hydroelectric projects during the June 2013 Disaster in Uttarakhand, April, 2014”*; submitted to Ministry of Environment and Forest by the expert). The flood flow was routed through a narrow cross section. Such a breach is known to augment the stream power, accelerating downstream incision (Montgomery et al., 2004). The geomorphic expression of accelerated erosion and deposition of flood sediments can be seen from the presence of thick piles of sediment along the wider river sections between Lambagarh and Govindghat villages and a narrow segment between Govindghat and Vishnuprayag villages.

It was surprising that no major sediment flux was contributed from the Alaknanda river. The sole contributor was the Khiro Ganga (a small tributary of the Alaknanda river) (Fig. 9). The wide “U” shaped morphology of the Khiro Ganga valley suggests that, in the past, glaciers descended well below their present limits (which at present terminate at >4000 m). Our field observations in the Khiro Ganga valley indicate the following. (i) Old and stabilized alluvial fans are resting on steeply dipping valley slopes. Scouring caused by cirque glacier-fed tributary streams transported large volumes of sediment particularly from the southern slopes. (ii) Further, toe erosion by the glacier fed streams destabilized the old landslide deposits in the Khiro Ganga valley. (iii) Fissures developed in the apices of these

Figure 7. Field photograph taken in June 2013 of Vijayanagar (Tilwara). Increased sediment flux in the low gradient segment of the Mandakini river led to the lateral migration of the river course (blue dashed arrow) that was responsible for lateral erosion and collapse of the unconsolidated river banks in the Mandakini Valley. Pre- flood river course is shown by black arrow,

Figure 8. A generalized map of the Alaknanda valley. Locations of different barrages in Mandakini and Alaknanda valley are shown by red rectangles. (I) Singolo-Bhatwari at Sitapur, (II) L&T and Kund, (iii) Vishnuprayag at Lambagar and (IV) Srinagar at Koteaswar. The dotted red ellipsoid roughly marks the area affected in the Alaknanda valley. Note that the affected areas lie immediately downstream of the barrages.

landslides facilitating the percolation of rainwater which reduced the shear stress, thus causing collapsing of the valley slopes during June 2013. (iv) In the upper reaches (above Khiri village >2800 m) the constricted river channel was overwhelmed by the sediment supply from the erosion of lateral moraines, that emanate predominantly from the south facing cirque glaciers, and a massive landslide (~400 m long and ~100 m wide) on the northern facing slope above the village (30°40'49.52N, 79°27'42.22E). (v) This led to the obstruction of the river course, thus creating temporary impoundments of sediment-laden water. Breaching of the obstructions caused high-density flood surges that gathered momentum as more sediments were added due to the scavenging of old landslides and alluvial fan deposits downstream. (vi) These sediments after reaching the Alaknanda river, were obstructed by the Vishnuprayag hydropower barrage. Had there been no barrage, the sediment laden floodwater would have continued as an unusually high intensity flood peak. The pre- (Fig. 9a) and post- (Fig. 9b) flood pictures of the Khiri Ganga valley demonstrate the sensitivity of the paraglacial terrain to unusual weather events (discussed below).

The devastated area lies in the Higher Himalaya (Lambagarh to Govindghat) and is geomorphologically located in the “*paraglacial zone*”. Since glaciers once operated in the paraglacial zones, these areas are not sediment limited. The Indian Summer Monsoon (ISM) exerts a profound control on erosion, hill slope processes, river discharge, and sediment flux particularly along the Southern Himalayan Front (Bookhagen et al., 2005). However, during abnormal

monsoons (as was the case in June 2013) violent rainstorms can cross over the southern orographic barrier and trigger extensive erosion (i.e. debris flows). According to Bookhagen et al., (2006), such events play an important role in the overall sediment flux toward the Himalayan foreland. The terrain north of Lambagarh in the Alaknanda valley can be considered a ‘*hot spot*’ (with respect to sediment availability) that is continuously adjusting to changing climatic and environmental conditions. Here the authors differ from the suggestion made by Valdiya (2014) that the Higher Himalayan domain (north of the MCT) offers a much better and relatively safer site for dams. We consider that, in fact, the higher Himalayan terrain should not be tampered with for any major hydropower projects because that terrain is least well studied in terms of (i) processes responsible for sediment production (glacial and paraglacial processes), and (ii) the sediment transport mechanisms from the Higher to the Lesser Himalaya (e.g. cloud burst, landslide or glacial lake breaching, seismic perturbation). It is certain that the terrain responds violently to unusual weather events as shown by events in the Khiri Ganga valley (Fig. 9). A similar phenomenon was observed during August 2010 in the Ladakh Himalaya (Juyal, 2010). Virtually all hydropower projects, which were located in the Higher Himalaya, were buried under debris after the June 2013 flood.

Around Srinagar: Srinagar was the second most damaged location in the Alaknanda valley. There are conflicting views on the role of the Srinagar hydropower project in aggravating the impact of

Figure 9. (a) Khiro Ganga valley before the flood and (b) after the flood. This valley, known for its rich biodiversity, was the major contributor of debris into the Alaknanda valley that caused colossal damage to the Vishnuprayag hydropower project barrage at Lambagar. The magnitude of geomorphic changes indicates the sensitivity of the paraglacial regions in the Himalaya to short-lived intense climatic event, as demonstrated by these pictures.

the flood. This is because the area flooded lies on the lower-most terrace which was inundated during the 1894 and 1970 floods respectively (Wasson, 2008; 2013; Rana et al., 2013). Here it is pertinent to mention that the past floods (viz. 1894 and 1970) impacted the entire Alaknanda valley, whereas the major damage caused by the June 2013 flood was focused at two locations where the river was obstructed by hydropower barrages: around Lambagarh/Govindghat villages and downstream of Srinagar barrage (Rana et al., 2013). There is a strong perception among the local residents that the flooding in Srinagar was caused by localized river bulking by the debris that were dumped at nine locations along the river bank (Fig. 10). Interestingly, the rise in the riverbed at a few locations below the barrage site was noted by the Srinagar hydro-power officials in their post flood assessment report although they ascribed it to the sediments that were transported from the upper catchment (above the barrage), evidently from the Mandakini valley and Chorabari Lake in particular. In order to ascertain the contribution of natural sedimentation versus man made (anthropogenic) debris, the research included geochemical fingerprinting of the flood sediments.

Geochemical characterization

Flood sediments were collected from the river channel between Chorabari- Kedarnath-Agastmuni (Mandakini Valley) to Srinagar (Fig. 3). Around Srinagar detailed sampling was carried out along the river channel including the debris from three locations. The major oxides were analyzed using X-ray fluorescence (XRF) (Axios, from Panalytical limited) following the standard protocol. The analytical precision at the 2-sigma level for major oxides is better than 5% (Shukla, 2011). Sediment characterization was carried out using the Chemical Index of Alteration (CIA, a quantitative measurement of the extent of chemical weathering of a rock or sediment (Nesbitt and Young, 1982) and was estimated based on the molecular proportion of major element oxides as shown below, where CaO* refers to the contribution from silicates:

$$CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$$

The use of CIA in identifying the provenance of flood sediment has already been demonstrated in the Alaknanda valley (Srivastava et al., 2008). Because of high relief and tectonic instability, physical weathering dominates in the Himalaya (Srivastava et al., 2008). It is expected that the majority of the sediments mobilized during the event of June 2013 were either from the physical weathering dominated paraglacial terrain or fresh landslides. Therefore, the original CIA values of the rocks contributing to the sediments could be considered as unaffected and likely to mimic the original rock values. The dominant lithology as mentioned earlier is gneissic and granite in the upper reaches with quartzite and phyllite rocks around Srinagar. Since the phyllites/shales have higher CIA values in comparison to the gneisses and granites (Taylor and McLennan, 1985) these two end members can be used to estimate the relative proportions of the two contrasting lithologies in the flood sediments.

The CIA values of the nine flood sediments in the Mandakini Valley range between 45 and 53 (Table 1) which accords well with the observed values for granitic rocks i.e. 45-55 (Nesbitt and Young 1982). In the Alaknanda valley around Srinagar, two major lithologies viz. quartzite (upstream of the barrage) and phyllite (downstream of

Table 1. Major cations used in ascertaining the Chemical Index of Alteration (CIA) and the percentage of phyllite in flood sediment around Srinagar. (F.S. = Flood sediment, M.S. = Muck sediment).

Sample Code	Location	Al ₂ O ₃ (%)	CaO (%)	K ₂ O (%)	Na ₂ O (%)	CIA	Phyllite (%)
MKN-1	Kedarnath	11.3	1.82	3.21	3.01	49.1	
MKN-2	Kedarnath	11.7	1.65	3.31	3.39	49.1	
MKN-3	Kedarnath	10.6	1.23	3.09	4.00	46.6	
MKN-4	Kedarnath	12.4	1.30	3.75	3.52	50.4	
RAM	Rambara	12.9	1.83	3.63	3.54	49.7	
SPN-1	Sonprayag	11.1	2.80	2.85	3.19	45.1	
AMN-1	Agastmuni	11.6	1.96	2.73	3.25	49.5	
ALAK-LOC-1	Srinagar (M.S.)	17.6	0.62	4.03	-	76.3	88
ALAK-LCO-2	Srinagar (M.S.)	19.9	0.68	4.41	1.26	71.2	71
ALAK-LOC-6	Srinagar (M.S.)	19.4	0.79	4.57	-	75.3	85
ALAK-LOC-3	Srinagar (F.S)	12.3	3.08	2.57	1.28	63.8	47
ALAK-LOC-4	Srinagar (F.S)	15.0	2.54	3.90	2.08	57.5	27
ALAK-LOC-5	Srinagar (F.S)	13.0	2.66	2.82	1.69	60.1	36
ALAK-LOC-7	Srinagar (F.S)	14.6	2.51	3.65	1.92	58.7	31
ALAK-LOC-8	Srinagar (F.S)	16.0	2.52	4.32	1.41	63.3	46
ALAK-LOC-9	Srinagar (F.S)	14.3	1.97	3.37	2.26	56.3	23
Quartzite		1.3	0.60	0.20	-	49.2	
Phyllite		15.4	0.48	2.76	-	80.0

Figure 10. DEM of Srinagar valley. Two contrasting lithologies, the phyllite in the southwest and quartzite in the northeast, are separated by the North Almora Thrust. Srinagar hydropower barrage is located on the quartzite dominated lithology. Phyllite percentage in anthropogenic debris (shown in red circled with red ellipsoids), phyllite percentage in the flood sediments (shown in black circled with black ellipsoid). Numbers in violet are the Chemical Index of Alteration (CIA). Implications of these numbers are discussed in the text.

the barrage) are separated by the North Almora Thrust (Srivastava and Ahmed, 1979). The CIA value of the quartzite sample is 49, whereas the phyllite's CIA is 80 (Table 1; Fig. 10). The CIA values of six flood sediment samples collected downstream of the Srinagar hydropower barrage range between 56 and 64 (Table 1; Fig. 10) suggesting a contribution from a clay mineral dominated lithology (Nesbit and Young 1982). The lower values in the Mandakini valley (45°53') accord well with the upper catchment lithology (granite, granodiorite and gneisses; Table 1) whereas the relatively higher CIA values below Srinagar barrage indicate a contribution from phyllite rocks that are widespread around Srinagar (Table 1; Fig. 10). The CIA fingerprinting of the flood sediments indicate an appreciable contribution from phyllite.

Here it is worth re-emphasizing that the debris generated during the tunneling, canal and power house excavation were disposed of at nine locations along the river bank, as noted earlier. Visual inspection of the debris indicates a dominance of phyllite that is also supported by high CIA values (between 76 and 71). Except in one location, all debris were dumped along the river bank downstream of the barrage. A study carried out by the "Alternate Hydro Energy Center, Indian Institute of Technology, Roorkee" on the cumulative impact of hydropower projects in Alaknanda and Bhagirathi basins up to Devprayag (volume-I, Chapter-4, pp. 4°69; 2011) had already raised concern about the way phyllite dominated debris were stored along the river bank. The report noted that *"the excavated material from open channels and the muck from tunnel excavation have been posing major environmental problems for their disposal. The muck presently disposed on the river bank without proper site selection and suitable precaution. This is causing addition of silt to the Alaknanda river throughout the year."*

This point proved to be correct because during the flood, ~450,000 m³ (from the university stadium dump) and ~50,000 m³ (from the Kotesawar dam colony dump) were eroded. Very similar observations were also made by Sati and Gahlaut (2013). Considering that the debris were dominated by phyllite, we used a two end member mixing model in which one end-member was freshly collected phyllite

(CIA-80) and the other was quartzite (CIA- 49). It was observed that the phyllite contribution to the flood sediment below the barrage and downstream of Kritinagar varied from 47% to 23% (Table 1; Fig. 10). This estimate remained the same even if we replaced the quartzite with that of the average CIA value of eight flood sediment samples collected between Kedarnath and Agastmuni (Table-1). This indicates an appreciable contribution of anthropogenic debris in raising the river bed (locally) during the flood. This inference is further supported by the K₂O/Al₂O₃ ratio that is used to differentiate between the clay and feldspar rich sediments (Cox et al 1995). The K₂O/Al₂O₃ ratio of clay rich sediment (phyllite) was between 0.0 and 0.3, whereas for the feldspar rich sediments (such as quartzite) it varied between 0.3 and 0.9. In the six flood sediment locations, this ratio varied between 0.20 and 0.26 (close to clay rich sediment) which further supported the suggestion that indeed there was a contribution from the phyllite-dominated anthropogenic debris.

Discussion and conclusions

In the recent past, there has been an increase in the frequency and magnitude of flash floods in the Uttarakhand Himalaya (Sati et al., 2011; Rana et al., 2013; Gupta et al., 2013). There are suggestions that under the "Warm Earth" scenario, unusual weather events would increase globally and that these might lead to increased flood frequency in the Himalayas. Geological evidences of past floods (e.g. slack/palaeoflood deposits) are scanty. However, some sheltered locations around Srinagar, Bhainswara and Devprayag (Fig. 8), have allowed an, at least, 600 year history of floods in the Alaknanda valley to be reconstructed (Wasson et al., 2008; Srivastava et al., 2008; Wasson et al., 2013). These studies indicate that most of the major floods were most likely an outcome of natural dam bursts in the upper Alaknanda catchment and the 1970 flood was the greatest in magnitude. However, during June 2013, the 1970 flood mark was surpassed near Srinagar and further downstream at Bhainswara (Fig. 8).

Detailed field mapping immediately after the 17th June 2013 flood

around Srinagar and downstream at Bhainswara by Rana et al. (2013) led to the following observations. (i) June 17th 2013 flood deposits invariably overlie the 1970 flood sediment and occur at an elevation of 536 m at ITI (the lower terrace at Srinagar) to 516 m at Bhainswara. (ii) During 1970 the highest flood mark was at 533 m at Srinagar and 511 m at Bhainswara. This implies that the June 2013 flood was the highest flood recorded below the Srinagar hydropower project barrage in the Alaknanda valley during the last 600 years (Rana et al., 2013). Contrary to this, the 2013 flood remained below the 1970 flood level upstream of Rudraprayag which was inferred from the absence of June 2013 flood sediment on top of the 1970 flood deposits that are preserved at Kaleshwar (Karanprayag), Chamoli, Chinka and at the confluence of Birehi Ganga and Alaknanda river (Fig. 8).

The past floods (at least those of 1894 and 1970) were associated with landslide-induced dam breaching. The recent flood in the Alaknanda valleys does not seem to fit into that category. Commercial deforestation in the region was banned since 1980 so it is unlikely that deforestation can be implicated in the June 2013 flood. If the rivers were not blocked by landslide dams what led to the generation of such a large quantum of sediment in the Mandakini and Alaknanda valleys? A definite answer to this important question may require a more detailed multidisciplinary study in the Himalayan region to arrive at a firm and meaningful conclusion. However based on the present study we are able to provide some answers to the questions we set in the background::

- (i) In the upper catchment of the Mandakini Valley (around Kedarnath) moraines left behind by receding glaciers and debris flow fans provided voluminous sediments. These sediments were transported by a combination of high intensity rainfall and steep gradient streams including the water released from Chorabari Lake. A significant quantum of sediments was arrested at Sonprayag and Sitapur villages. Further downstream, the sediment bulking was caused largely by landslides and to some extent by the contribution from the hydropower muck dumped around Kund and Vijaynagar. In the lower reaches, where the valley gradient is more gentle, sediment laden flood water was temporarily obstructed by the man-made structures particularly the partially constructed barrages and the human settlements that encroached upon the river bed. The sediment bulking was responsible for the amplification of the flood magnitude and lateral migration of the Mandakini river that caused lateral bank erosion and collapsing of unconsolidated slopes below Kund and Tilwara in the Mandakini valley.
- (ii) The destruction between Lambagarh and Govindghat was increased by the obstruction to the high intensity debris flow caused by the barrage. It seems that the project proponents failed to appreciate that floods generated in the paraglacial domain are highly peaked and carry large volumes of debris that can pose a serious threat to the safety and longevity of the power projects as demonstrated during the recent flood. The present study, therefore, suggests that the paraglacial zone (Higher Himalaya), should not be subject to any major human intervention, particularly for harnessing hydropower. However, in areas where such projects are essential, these should be tuned to the terrain boundary conditions, particularly taking into consideration the various environmental, ecological and social constraints within the entire catchment above the project locations.
- (iii) Around Srinagar valley, the study demonstrates that the

anthropogenic debris was one of the major factors in aggravating the flood magnitude. Geochemical analysis indicates that the contribution from those debris to the June 2013 flood varied from 47% (proximal to the barrage) to 23% (distal location below Kirtinagar).

Therefore, it cannot be a mere coincidence that maximum destruction of land and property was narrowly focused in areas proximal to hydropower projects. In our opinion, the June 2013 tragedy should be an eye-opener to policy planners, particularly the proponents of hydropower projects. They must re-evaluate their methods because the high mountains are particularly sensitive to extreme rainfalls during which floods can incorporate huge amounts of sediments.

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