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Geo-environmental consequences of obstructing the Bhagirathi River, Uttarakhand Himalaya, India

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\textbf{ABSTRACT}

The Bhagirathi Valley is investigated to understand the impact of various barrages and dams on natural river flow. The multiple barrages and dams in the valley (downstream of the Bhatwari Village) have obstructed/disrupted natural flow of the river which has adversely impacted geomorphological and ecological functions of the river. Besides, it is observed that during and after the implementation of the hydropower projects, the terrain stability was severely affected due to creation of fresh landslide zones, destruction of forest and rural infrastructures including the marginal agricultural lands. The study observes that lack of detailed geological, geomorphological and ecological investigation prior to the execution of the hydropower projects led to the terrain instability. Further, dearth of detailed scientific studies was responsible for the lack of comprehensive engineering/bioengineering measures and catchment area treatment plans as also the measures for reservoir rim slope stability. Taking cognizance from the Bhagirathi valley, present study calls for a detailed multidisciplinary study in the Himalayan valleys where the rivers are likely to get impounded for harnessing hydropower.

\textbf{1. Introduction}

The Himalaya, one of the youngest orogenic belts and ecologically sensitive terrain is severely impacted by soil erosion, landslides, and flash floods. The recent most example is the June 2013 Uttarakhand Disaster which not only took a heavy toll on life but also severely damaged various hydropower projects in the region (Theopheophilus, 2013; Sati and Gahalaut 2013; Ravi Chopra Committee report 2014; Sundriyal et al. 2015). Studies suggest that the majority of the Himalayan floods originate in the vicinity of the southern flank of the Higher Himalayan Crystalline (HHC) also known as the southern mountain front. These floods are largely associated with the Landslide Lake Outburst Floods (LLOFs) (Kimothi and Juyal 1996;
There is a global concern about rising frequencies and magnitudes of the flash floods (extreme hydrological events) impacting life and infrastructure (Working Group-I, IPCC, 2013). The southern mountain front is known to arrest the Indian Summer Monsoon (ISM) and thus, generate focused torrential precipitation (Bookhagen et al. 2005). Until the late 1970s there was no major intervention in the Himalayan river valleys to harness the hydropower potential and thus, construction of dams and barrages was limited. Therefore, it was suggested that prior to the 1970s, flash floods were largely due to the natural processes (extreme weather events), an exception being the July 1970 Alaknanda flood, which was a classic example of large-scale commercial deforestation in the southern mountain front (Kimothi and Juyal, 1996; Rana et al., 2013). Since the Himalayan floods not only carry water, and energy but also transport an enormous quantity of sediments (Bandopadhyay and Ghosh 2009); understanding the pattern and magnitude of past floods in the Himalaya becomes extremely important for designing the environmentally viable and economically sustainable hydropower projects (Sundriyal et al. 2015).

For the viability and longevity of hydropower projects, long-term flood data is crucial to understand the behavior of a river and also to devise a methodology to safeguard barrages, dams and related infrastructures. In the Himalayan region, there is a paucity of longer flood records and therefore, to extend the instrumental archives, sedimentological evidence of past floods – slack water/palaeo-flood deposits are used (Wasson et al. 2008; 2013; Sharma et al., 2017). However, in monsoon dominated and tectonically active central Himalaya, these deposits are difficult to locate due to limited preservation potential. Wasson et al. (2008; 2013) reconstructed 1000-year history of floods in the Alaknanda valley using sedimentological evidence and suggested that the majority of the floods were generated by LLOFs with a dominant source in the Higher Himalayan region. The 1970s Alaknanda flood is a recent example of such natural dam burst which is also known to be the highest flood in the last 100 years (Kimothi and Juyal 1996; Rana et al. 2013). The flood magnitude was augmented because of commercial forest felling in the upper catchment of the Alaknanda River (Kimothi and Juyal 1996). Since the 1980s, commercial forest felling has stopped in the Uttarakhand Himalaya and thus, the coupling between deforestation and flash floods can be discounted. However, in recent years the terrain is tempered by rampant proliferation of the hydropower projects. These projects have not only rendered the Central Himalaya susceptible to slope instability but have also obstructed the free flow of the rivers, particularly during extreme weather events such as the June 2013 Uttarakhand Disaster (Sati and Gahalaut 2013; Sundriyal et al. 2015 and references therein). There is a growing concern that Himalayan region is extremely vulnerable to global warming (Sati and Raiwani, 2016 and references therein). The recent IPCC Special Report (2018) indicates that human activities are estimated to cause ~1.0 °C rise above pre-industrial levels, with a likely range of 0.8 to 1.2 °C. If the trend continues, the temperature rise is likely to reach 1.5 °C between 2030 and 2052, and is expected to impact ecosystems with long-term and/or irreversible damage along with the increase in intensity and frequency of extreme weather events.
Under such a scenario, if the water resources are to be harnessed, one must also be cautious of the contribution from the glacial-fed rivers in the Himalaya. It is likely that the glacier mass balance (melting/accumulation) would change significantly and unpredictably due to variable response time of the glaciers (size, orientation, precipitation amount, etc.) to the projected warming.

Therefore, it is pertinent to include the state-of-the-art scientific studies pertaining to climate change in the river valley projects. Most importantly, scientifically rigorous Environmental Impact Assessment (EIA) study seems to be lacking pertaining to the execution of river valley projects in the region. Specifically, there is no elaborate discussion on the zones which might be affected after the commissioning of the projects (collateral damage). Therefore, in order to minimize the impact of the project on the land and the people, there should be a detailed section in EIA on the aspects of collateral damage so that appropriate remedial measures can be carried out well in advance. Recently, Sati et al. (2019) have discussed that if mega hydropower projects defy the terrain boundary conditions and are not blended with rigorous scientific scrutiny, it might lead to significant collateral damage, and thus affecting the terrain stability and sustainability of the local inhabitants. The present study is therefore, in continuation of the efforts to understand the causes, nature, and extent of collateral damage caused by the hydropower projects in the Bhagirathi valley. Considering that several hydropower projects are being planned in the Himalayan region in general and Uttarakhand in particular, a prior discussion may help in facilitating the reduction of the impact on ecologically sensitive terrain, if it cannot be avoided entirely.

2. Study area

The Bhagirathi valley is sculptured by the Bhagirathi River and its tributaries. The river originates from ~32 km long Gangotri Glacier (4255 m asl) and is fed by around thirty tributary glaciers. The river traverses a distance of ~200 km before it meets the Alaknanda River at Devprayag (465 m asl). From here onwards it is called the Ganga River (Figure 1). Currently, there are 20 hydropower projects on Bhagirathi river which are at various stages of planning, under construction and operation (source: http://uttrakhandjalvidyut.com/new/hydropower-project-in-uttrakhand). The geological and geomorphological investigation carried out during the course of the present study in the Bhagirathi valley indicates that there are certain areas/valleys which are chronic in terms of terrain instability, and require utmost care.

2.1. Geology and geomorphology

The Bhagirathi valley has four major lithotectonic units separated by the terrain boundary thrusts. From north to south these are the South Tibetan Detachment System (STDS) that separates the Tethyan sedimentary succession (exposed to north of Bhairo Ghati Gorge) from the Higher Himalayan Crystalline (HHC) rocks till the Bhatwari Village. The HHC is separated from the meta-sedimentary succession by the Main Central Thrust (MCT) (Figure 2). The meta-sedimentary succession is dominated by quartzite and phyllite with subordinate dolomites and continues till the
confluence with the Alaknanda River at Devprayag and beyond (Prasad and Rawat 1978).

Detailed geomorphological observation carried out during October 2017 shows that the terrain above 2000 m is influenced by paraglacial processes whereas, above ~4000 m the glacial processes dominate that accords well with the earlier studies (Barnard et al. 2004; Singh et al., 2017). The Gangotri Glacier is not only the biggest glacier in the Uttarakhand Himalaya, but it is also the largest producer of glaciogenic sediments (moraines) (Sen et al., 2016) (Figure 3). The relics of moraines, representing the past glacial expansion are observed around the Jhala village – a distance of ~40 km from the present-day glacier snout (Sharma and Owen 1996). Owing to the

Figure 1. The drainage map of Bhagirathi river showing the distribution of proposed, under construction and completed hydropower projects. The Loharinag Pala is scrapped and Pala Maneri is deferred. Note the high concentration of barrages (bumper to bumper) between Harsil and Gangotri. Presently the large part of the river section is already inundated and if all the proposed projects become reality, the river will virtually be diverted into tunnels. Source: http://matuganga.blogspot.com/2011/12/dams-in-ganga-valley.html
large paraglacial area (between the snout and Jhala village), the upper (snout proximal) reaches of the Bhagirathi valleys are not sediment limited (Figure 3).

The Indian Summer Monsoon (ISM) provides most of the 1550 mm annual precipitation (Barnard et al. 2004) whereas; the microclimate is controlled by the valley aspect, proximity to glaciers, and altitude (Sharma and Owen 1996). Due to fluvial incision and heavy monsoon precipitation, sediment mobilization is common in the paraglacial zone of the Bhagirathi Valley (Barnard et al., 2004). Below the paraglacial zone, the slope instability is triggered by the focused rainfall during the summer as ISM is obstructed by the southern mountain front (geomorphic expression of MCT). The lithology is highly fractured, crushed, and pulverized that is capable of generating
massive landslides and LLOFs thereof in the physiographic transition zone (Wobus et al. 2005; Wasson et al. 2013; Sharma et al., 2017).

2.2. Anthropogenic intervention

The Bhagirathi River is fragmented due to the existing commissioned hydropower projects such as the MBP-I, II, Tehri, and Koteshwar Dams (Figure 1) which at places have rendered the mighty glacial-fed river as a mere seasonal stream. According to the Ravi Chopra Committee report (2014), out of 217 km stretch of the river, around 70% (average) is fragmented due to the obstruction caused by plenteous hydropower projects.

The concern about the poor health of the river echoed in the government of Uttarakhand as well. However, they implicated “continuous and phenomenal increase in human and cattle population and the anthropogenic pressure on ecosystems which is causing irreparable damage to the fragile mountain ecosystems including flow and character of the Bhagirathi river” (Zonal Master Plan-MoEF 2012, page 17). It is astounding that even after witnessing multiple disasters in the Bhagirathi valley, viz. Kanodia Gad landslide lake outburst (1978), Varnawat Mountain Slide (2003), Bhatwari Landslide (prior to 1991), Asi Ganga Disaster (2012) and extreme hydrological event (June 2013), we fail to appreciate the ecological sensitivity of the Bhagirathi valley.

3. Terrain instability due to landslides and hydro-power projects

3.1. Kanodia gad landslide

On the midnight of 6th August 1978, a massive landslide in the MCT zone obstructed the Bhagirathi river (Prasad and Rawat 1978). The landslide was triggered in the paraglacial zone of Kanodia Gad (rivulet) (around Gairaridhar; ~4000 m) and travelled a distance of ~4 km to the confluence of the Bhagirathi river where it blocked the river for about 14 hours. Around 175 m wide rampart of rocks and debris formed a lake 35 m high, 45 m wide and ~3 km in length (Figure 4). The water began to overtop the landslide dam on 10th August and the breaching occurred on 11th August 1978 that caused large-scale downstream destruction (Agarwal and Chak 1991). Since then the paraglacial zone around Gairaridhar is unstable and occasionally blocks Kanodia Gad leading to minor flood pulses. The remnant of the landslide debris can still be seen, which has transformed the channel morphology from a reasonably wide confluence to a constricted passage for the Bhagirathi river (Figure 4).

3.2. Asi ganga disaster

On 3rd August 2012, a massive devastation occurred in the Asi Ganga valley due to a cloudburst at the orographic barrier (around Pandrasu Dhar ~4500 m). The river meets Bhagirathi river at Gangori village and drains through highly crushed lithology of HHC and the Lesser Himalayan meta-sedimentary rocks. The debris-laden slopes were precariously resting over the steep bedrock and the narrow confines of the Asi
Ganga valley through which the flood water gushed during the torrential rain on 3rd August 2012 (Figure 1). The hyper-concentrated debris-laden water laterally scoured the stabilized landslide deposits, and inflicted a severe blow on the built structures along the way. During the flood, Asi Ganga far exceeded the normal discharge of 100–200 m³/s to >2500 m³/s that is similar to the Bhagirathi River water discharge (Gupta et al., 2013). According to Gupta et al. (2013) the flash flood completely damaged the three small under-construction hydro-power projects (Asi Ganga-I, Asi Ganga-II and one in the Kalidi Gad). The complete road network from Gangori to Dodital was disrupted and ~10 km of the road was completely washed away. Besides, there was damage to the flood protection wall on the left side of Asi Ganga in the Gangori township. As the river was trying to adjust to the new channel morphology, a second cloud burst in June 2013 transformed the landscape into a desolate river, strewn with boulders and debris. Asi Ganga is presently a river of boulders than water (Figure 5). The pertinent question is that if the impact of the cloud burst was amplified due to the obstruction caused by the buildup structures particularly the hydropower projects and the roads constructed for the transport of constructional material? Was the amplification of discharge to >2500 m³/s from 100–200 m³/s in a small stream solely due to high precipitation, or was it a cumulative effect of water accumulation behind temporary dams made by slope destabilization and obstruction of the hydropower structures? These questions still remain unanswered.

3.3. Bhatwari landslide zone

The Bhatwari village and its adjoining areas are in the vicinity of the MCT which marks a transition from the high-grade metamorphic Greater Himalayan sequence in the north to the lower-grade Lesser Himalayan sequence in the south. As mentioned above, MCT also dictates the physiographic transition between the southern lesser Himalaya and northern higher Himalaya. The erosion rates estimated on ³⁸⁷⁷Be are higher in the physiographic transition and reveal a sharp discontinuity compared to its southern and northern Himalayan counterparts (Wobus et al. 2005).
prompted Wobus et al. (2005) to invoke the presence of a tectonically significant, thrust-sense fault zone at this transition which is ascribed to strong dynamic interactions between climate, erosion, and tectonics. The presence of deep-seated landslides around Bhatwari indicates geomorphic vulnerability of the area which was adversely impacted by 1991 Uttarkashi earthquake. A team headed by Dr. A.K. Jain from Roorkee University visited Uttarkashi after the earthquake and made the following observation, “Numerous massive landslides took place on the Uttarkashi-Harshil road, particularly on a 42 km stretch between Uttarkashi and Bhatwari. The stretch is believed to be the area of most intense shaking. While landslides on this route are common in rainy seasons, many of the landslides caused by the earthquake were totally new. Deep fissures on the road caused by the earthquake pose a potential threat of slope failure in the near future. Fissures were most prominent on the Maneri to Bhatwari stretch” (Jain et al. 1992). Ignoring the fact that the area is susceptible to earthquakes and the terrain is highly degraded, 600 MW Loharinag-Pala Hydro-power project was planned below the confluence of the Songad River around 60 km upstream of Tehri dam. The majority of the structures such as HRT (Head Race Tunnel) and the underground powerhouse were concentrated (or constructed) between the Kanodia Gad landslip and extremely unstable slopes around Bhatwari village. Currently, the area is reeling under frequent land subsidence (Figure 6(A,B)) particularly after 2006, when the work on the headrace tunnel for Loharinag-Pala was
initiated. Fortunately, the work on the project was stalled in 2009 due to strong protest spearheaded by the late Prof Professor G. D. Agarwal. But till 2009, much damage to the terrain and environment was already done as can be seen by the presence of degraded slopes, landslide scars and frequent slope instability (Figure 6(A,B)). Here it is important to mention that the Bhagirathi valley (~100 km stretch), between Uttarkashi to Gangotri (~100 km) was declared as an eco-sensitive zone (ESZ) on December 18, 2012 under the Environment Protection Act, 1986. Thus, barring the construction of power projects > 2 MW besides prevention of water for industrial purposes, quarrying and mining, blanket ban on felling of trees, etc. (Basu 2015).

3.4. Maneri Bhali Phase-II (MBP-II)

The hydropower projects require excavation of tunnels which many times cause slope failures, land subsidence, and disrupt the groundwater fed village water springs and streams. Further, it is difficult to modify the construction method and support system

Figure 6. (A) and (B) two pictures of Bhatwari settlement after 2010 extreme rainfall and during the winter of 2014. Since then there is no respite as the slopes are continuously creeping. What was really worrisome that the Loharinag-Pala project power house was coming up just above the town.
in accordance with frequently changing lithology and local groundwater conditions. Therefore, tunneling in the Himalayan terrain with spatially diverse and frequently changing geological and hydrological conditions, rock blasting method is not a foolproof technique and can lead to slope instabilities and disruption of the aquifers (Goel et al. 1995). According to Goel et al. (1995), during the excavation of Maneri Bhalı Phase-I (MBP-I) tunnels (located upstream of Uttarkashi) faced problems of face collapse with or without heavy ingress of water, cavity formation, and buckling of steel ribs due to ground squeezing. The MBP-II project is fed by a 16 km long and 6 m diameter Head Race Tunnel (HRT). The HRT receives water from ~80 m wide barrage constructed on the Bhagirathi River at Joshiyara (Uttarkashi). The HRT of MBP-II passes above the Gunıyala village. The villagers observed a gradual decrease in the discharge of Kedi Gad (flowing east of the village) during the excavation of HRT (Figure 7). After the completion of the HRT, Kedi Gad became virtually dry and the water flows only in the lower reaches of the rivulet (below the village) (Figure 7(A,B)).
Geological and geomorphological investigation around Kedi Gad indicate that the lithology is dominated by fractured Quartzite with scanty alluvium cover. The Kedi Gad is a small rivulet that emerges from the northern slope of the village covered with pine forest in the lower reaches and low-density oak forest above ~1500 m. The upper slopes act as recharge areas for the rivulet during the monsoon. We hypothesize that the HRT has dissected the Quartzite in the middle segment and created an artificial impervious dyke thus, obstructing the subsurface flow. Since the 1991 Uttarkashi earthquake, no major seismic activity occurred in the region. Therefore, the presence of large boulders in a small seasonal stream can only be attributed to a process that facilitated the detachment of the rocks from parent lithology and their subsequent downstream sliding by gravity. The process is obvious on steep mountain slopes given the liberal use of explosives during the excavation of the HRT as observed by the villagers. Our investigation suggests that the slopes below the HRT are plugged with the excavated Quartzite boulders beneath which some water is flowing. The stream reappears below the motor bridge where the Kedi Gad flows through the bed-rock section having no sediment apron (Figure 7(A,B)). Therefore, the drying of Khedi Gad and the construction of HRT cannot be a mere coincidence. This is a classic and rare example of drying up of the stream by clogging it through the debris generated by the tunneling activity. Locals informed that there are a few more villages through which the HRT passes and which are suffering from similar problem. Besides this, near the tail trace tunnel (powerhouse) a huge landslide was triggered after the 2013 disaster which has become a chronic problem for the safety of the powerhouse.

3.5. Tehri dam reservoir

The dam (260.5 m) located on the Bhagirathi River near Tehri town (now submerged) is the highest dam so far in the Indian Himalaya (Figure 8). The dam has submerged 44 km stretch of the Bhagirathi River valley and 25 km stretch of the Bhilangana...
River valley which translates into a reservoir area of $\sim 42 \, \text{km}^2$ (Rana et al. 2007; International Hydropower Association, 2017). It has a maximum reservoir level (MRL) of 830 m and the dead storage level (DSL) is 740 m (International Hydropower Association, 2017). The submergence area which lies between the dam at Tehri and Chinyalisaur ($\sim 44 \, \text{km}$ upstream) was once occupied by fluvial deposits/terraces. According to Sundriyal et al. (2009), five levels of well-developed valley-fill terraces were preserved in the Bhagirathi valley between Tehri (now submerged) and Dharasu (Figure 1). Texturally the terraces were moderately compact, dominantly clast supported with subordinate sand. The oldest and highest terrace T5 was the thickest ($40 - 50 \, \text{m}$) and occurred between 300 to 400 m above the river bed (Figure 9) which now protrudes out from the reservoir rim and constitutes a distinct geomorphic entity along with the alluvial fans and debris flow deposits. In addition, innumerable monsoon fed streams which sustained the irrigated agricultural fields in the lower valley, now suffer from the backwater inundation during high reservoir level. Once the reservoir level is lowered these valleys are filled with the slack water sediments (Figure 10(F)). Many villages are on the terrace T5 flanking the northern margin of the reservoir rim area (viz. Bhenga, Jangi, Chaundhar-Matna, Nakot, Chanthi, Jhinmoli, Raulakot, Jhadka-Dogda, Nautad, Madan Negi and Sandna-Khand). The textural attributes (boulders and sand) and the unconsolidated nature of fluvial terraces make them highly porous and permeable during frequent changes in the reservoir level.

Since the maximum drop in the reservoir level goes up to $-90 \, \text{m}$, this would imply that $-90 \, \text{m}$ of the valley slopes covered with debris are supersaturated during the MRL. Anbalagan and Kumar (2015) and Kumar and Anbalagan (2015) have modelled the hydraulic process taking into consideration the geological and geomorphological boundary condition around the Tehri dam reservoir rim area. According to them, during the MRL, in the submerged debris slopes, the weight of the debris is reduced due to the buoyancy effect; however, the lateral reservoir water pressure prevents the debris...
from sliding. Whereas, when the reservoir water lowers during the DSL, the reservoir slopes get differentiated into (i) an upper dry zone, (ii) middle water saturated zone and (iii) lower water submerged zone (Figure 1(b) of Anbalagan and Kumar (2015). As the water lowers during the DSL, the weight of the debris increases temporarily till the water funnels out from the saturated zone. As this happens, the debris becomes weak in its cohesiveness due to the significant reduction in the shear strength. This leads to the slope instability which is manifested by the occurrences of land subsidence and landslides. Similar to the observation made by Anbalagan and Kumar (2015), we also observed arcuate shaped subsidence on the northern fringe of the reservoir between 100 m to >1000 m typically associated with the debris slopes. Such subsidence is caused due to the readjustment of the repose angle to new equilibrium condition which in the

Figure 10. Collage showing the nature of collateral damage on the northern flank of the reservoir around Mohan Negi village. (A) fissured and displaced agricultural field, (B) fissured metalled road (C) and (D) damaged houses (E) debris flow fan emanating from the southern tributary streams are engraved with strand lines indicating fluctuating reservoir level and (F) after the back filling of water during high reservoir level, as the water recedes, it leaves the slack water sediment rendering the lower fertile slopes unproductive.
preset case is the changes in the height of the supersaturation condition modulated by changing height of the reservoir water level. The progressive nature of these landslides has become a major threat to the population settled in the upper reaches of the slopes (Kumar and Anbalagan 2015; Sati et al. 2019). Similar observation was made by Sati et al. (2019) suggesting that the Reservoir Drawdown Effect (RDE) is one of the major geomorphic threats to the terrain stability in the Himalaya. According to them, the slopes around the dam reservoir are yet in the process of adjusting to the new hydro-meteorological conditions since 2006 (after the filling). Other geomorphological studies around the large hydropower projects have also shown that majority of the slope failures around the reservoir rim and upstream slopes were associated with the RDE (Sherard et al. 1963; ICOLD 1980). It is also feared that the impounding of the flow behind large reservoirs like Tehri dam is likely to perturb the local hydro-meteorological conditions by increasing the atmospheric moisture which also act as a greenhouse gas. Rising temperature would lead to more evaporation from reservoirs which would absorb more thermal infra-red energy radiated from the Earth, and thus, further warming the atmosphere (https://www.ncdc.noaa.gov/monitoring-references/faq/greenhouse-gases.php#h2o). A report published in The Hindu 2014 (https://www.thehindu.com/news/national/other-states/article5665439.ece)) reported that ~80 villages around the Tehri dam reservoir are reeling under constant threat of landslides/subsidence and soil erosion. Kumar and Anbalagan (2015) raised the concern about the increasing frequency and variable magnitude of slope failures in and around the Tehri dam reservoir. They mapped ~150 landslides having dimensions varying between 25 and 3000 square meters which were caused due to the combination of rotational, planer and the talus slope failures. These are attributed to the RDE with ~50% located in the reservoir rim fringe. Rautela et al. (2002) using remote sensing, estimated that the Tehri dam reservoir in the upper catchment would impact ~2687 hectares of agricultural land and around 3347-hectare land around the reservoir rim would be rendered unfit for agriculture. Here it is important to note that this study was conducted before filling of the reservoir. A recent report by International Hydropower Association and London (2017), made a startling revelation that during the planning phase of the dam, there was no sediment management strategy to route or remove sediment from the reservoir. Also, lack of sedimentological data hindered accurate estimations of the sedimentation rate. According to the above report, two bathymetric surveys were conducted after the commissioning, one in 2008 and second in 2013. Based on these surveys, the sediment load in the reservoir was estimated at 0.01 Mt per year whereas, a satellite-based study conducted in 2011, observed the loss of storage capacity. This led to the initiation of the Catchment Area Treatment (CAT) plan in areas that are subjected to high to very high erosion (~52,000 hectares, which includes 44,157 hectares of forest land and the 8,047 hectares of agricultural land). The soil erosion in the rim area of the reservoir is monitored between 850 and 1,050 m altitude. The intervention which should have been initiated well before the commissioning of the project was implemented after the commissioning, that too in a fire fighting manner. We do not see any appreciable and visible impact of CAT around the reservoir rim area, simply because the slope needs to be stabilized which after filling of the reservoir is extremely difficult due to the RDE (discussed above).
A collateral damage policy by the Uttarakhand government was formulated to rehabilitate these villages around Haridwar, Rishikesh, and Dehradun. However, Tehri Hydro Development Corporation Limited (THDC) was of the opinion that rehabilitation should be in the vicinity of the dam reservoir. In this conflict, nothing materialized on ground and the affected villagers are still caught in the tussle between the THDC and the State government. We also observed that the majority of the land subsidence and slope failures are occurring between 800 to <1000 m altitude (Figure 10). For example, in Okhala village (30° 27, 29.3°N and 78° 26’35.3°E; elevation ~1000 m), it was observed that the agricultural fields are fissured and houses have developing cracks (Figure 10(A–D)). According to the villagers, the slope instability was triggered after filling of the reservoir. Here it is important to mention that the fissured fields are located on the debris resting over a stable N-S trending spur in the upper reaches which is the northern watershed divide of the ester while Bhagirathi river (Figure 10(A)). The debris laden southerly slopes on which the agricultural fields are terraced extended below the reservoir surface before filling and now extend up to the fringe of the reservoir. Although there is no way to check the claim made by the villagers of when actually the subsidence began, however, it is important to note their observation, i.e., the subsidence occurs not when the reservoir is filled but when the reservoir level is lowered. Hence matches with the RDE identified in the scientific studies.

There is no denial that the reservoir rim is riddled with innumerable landslides which appear quite fresh suggesting that the slopes are in the processes of adjusting to the new hydro-meteorological conditions. Will that ever be achieved in tectonically active terrain like the Central Himalaya? There seems to be no answer for this question at the moment. Due to various operational reasons water level in Tehri dam reservoir is bound to fluctuate, thus with changing inflow-outflow conditions the fluvial terraces and debris-laden valley slopes are likely to respond unless protected by effective engineering bio-remedial measures. There was a detailed blueprint prepared by the Geological Survey of India (GSI) in 1999, in which different categories of vulnerable zones were meticulously identified around the reservoir rim. If the THDC would have been proactive and implemented the GSI report before the filling of the reservoir, damage to the terrain and the people would have been minimized.

### 3.6. Koteshwar dam

The Koteshwar is a gravity dam which is 97.5 m high and 300 m wide. The reservoir area is spread over ~29 km² (source: [https://en.wikipedia.org/wiki/Koteshwar_Dam](https://en.wikipedia.org/wiki/Koteshwar_Dam)). This dam is constructed ~22 km below the Tehri dam on the Bhagirathi River (Figure 1). The project was approved in 2000 and commissioned in March 2011. A massive flood in September 2010, inflicted enormous damage to the project, particularly the diversion tunnel was blocked due to collapse of a hill. Besides this, after the filling of the reservoir, condition similar to the Tehri dam is being experienced by the villagers albeit lesser in terms of the number of villages affected.

We investigated one of the most severely affected Payal Village located in the western margin of the Koteshwar dam reservoir rim (Figure 11(A)). While climbing up to
the village, NE-SW trending fissures were observed on phyllite dominated colluvium, while the narrow path leading to the village subsided at multiple locations. The houses showed cracks, dislocated joints, differentially dislocated/tilted courtyard boundary walls (facing the reservoir), and laterally displaced/subsided RCC lined irrigation canal (Figure 11(B–D)). According to the villagers, the subsidence and destruction of their houses began after September 2010 when the Koteshwar reservoir water was released by THDC. Additionally, other surprising fact was that the three exploratory tunnels of length 80, 70 and 60 m trending NE-SW excavated below the Payal village were not adequately filled before filling of the Koteshwar dam which may pose a serious threat to the village. The stream power analyses which is an indirect indication for a river to perform its geomorphological/hydrological processes suggest that

Figure 11. (A) Upstream extension of the Koteshwar dam reservoir. Picture taken from the Payal village which is reeling under subsidence. (B) Damaged house walls (C) tilted boundary wall and (D) displaced irrigation canal. All these destructions are located facing the reservoir. Source: Author.
the virgin stretch of the Bhagirathi river is preserved only above MBP-I and below the Koteshwar Dam (Prakash and Kumar 2018). This would imply that the river is virtually dead with respect to performing the geomorphological and ecological functions between MBP-I and Koteshwar Dam (Agarwal et al., 2018) (Figure 1).

4. Conclusion
In the foregoing, we have tried to highlight the sensitivity of the Bhagirathi valley to human intervention. Our definition of human intervention refers to the large-scale tempering of the river valleys for injudicious exploitation for hydropower energy, ignoring the fact that Himalayan Rivers besides carrying the hydropower also transport an enormous quantity of sediment (Bandopadhyay and Ghosh, 2009).

The commissioning of medium and large hydropower projects such as MBP-I/II, Tehri, and the Koteshwar dams have impacted the lives of the people adversely who resided above the submergence altitude of Tehri and Koteshwar dam projects and are not adequately protected and compensated for the collateral damage. One of the reasons being, collateral damage policy is not dictated by the geological and geomorphological consideration, but by the height above the reservoir rim. We therefore, suggest that there is an urgent need for (i) the hydropower authorities must be entrusted with broader accountability for the safety and security of the people after the commissioning of the projects. (ii) Rejuvenation of the terrain destabilized by the construction of the projects and preservation of local water sources must be part of the policy. (iii) There should be a detailed multidisciplinary scientific study of the terrain likely to be submerged/affected by the power projects so that the collateral damage occurred in the Bhagirathi valley is not replicated. (iv) The height above the reservoir rim should not be the only criterion for the consideration of collateral damage caused due to the RDE; instead it should rely upon the geological, geomorphological, ecological and anthropological consideration.

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