Environmental implications of Pancheshwar dam in Uttarakhand (Central Himalaya), India

S. P. Sati, Shubhra Sharma, Naresh Rana, Harsh Dobhal and Navin Juyal*

The present study outlines major concerns and potential environmental consequences of the proposed Pancheshwar high dam in Uttarakhand (Central Himalaya), India. We evaluate the risks associated with the project in the light of environmental impact observed for the Tehri project in the region and the geological understanding developed over the years. Three major factors and their likely impacts analysed relate to (i) sediment mobilization from glacial–paraglacial zones and unstable slopes, (ii) infrastructure development, and (iii) seismicity. We highlight the need to reassess geo-environmental implications of the project in the ecologically sensitive Kaliganga valley.

Keywords: Environmental impact, Pancheshwar, reservoir draw down effect, sediment flux, seismicity.

THE convergence of Indian and Eurasian plates not only created the world's tallest mountain range – the Hindu Kush Himalayas (HKH), but also led to the rupturing and differential dislocations of rocks along the terrain bounding thrusts. From north to south, these are the South Tibetan Detachment System (STDS), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT)[1] (Figure 1). These thrusts also govern the altitudinal variability (mountain topography) and lithological discontinuities in the Himalayan region. The topography dictates the precipitation pattern across the Himalaya with two distinct high rainfall domains located to the south of MBT and MCT.

According to the report of the Ravi Chopra Committee[2] on hydropower projects in Uttarakhand Himalaya, the government plans to harness ~27,000 MW of potential hydropower from its rivers by constructing ~450 hydropower projects. Currently 92 projects with a total installed capacity of ~3624 MW have been commissioned and ~38 projects are under construction. According to a study[3], if the number of proposed hydropower projects planned on 28 major river valleys becomes a reality, the Indian Himalaya will have one of the highest average dam densities in the world (one dam for every 32 km of a river channel). Further, the feasibility and economics of large storage dams versus the smaller run-of-river projects are being debated in recent times[4,5]. The run-of-river projects rely on seasonal water availability while the storage dams store large volumes of water to be used when the river discharge diminishes.

If we look into the nature of distribution of the proposed hydropower projects in Uttarakhand, nearly 22 are planned above 3000 m elevation in paraglacial zones (areas vacated by the glaciers), 44 are between 3000 and 2500 m (between paraglacial and winter snow line zone), whereas 54 are proposed between 2500 and 2000 m elevation (around the zone of winter snow line). This implies that the projects would largely populate the higher Himalayan region where the MCT represents a wide zone (5–20 km) of crushed and fractured lithology (myolinitized rocks). It is seismically active with maximum strain build-up and concentration of moderate earthquake epicentres[6,7] (Figure 1). Recent studies on Indian Himalaya based on the geological records of floods extending back to Early Holocene[8–11] suggested that mega floods were predominantly generated in the Higher Himalayan region. This vulnerability and the risk associated with disasters like earthquakes and floods is increased manifold by the construction of mega storage dams with the progression of dam age[12–14].

With this backdrop, the present study attempts to assess the potential geo-environmental impact of the Pancheshwar high dam proposed on the Kali river. The study focuses on evaluating the environmental consequences in view of the current understanding of Himalayan rivers with respect to sediment mobilization, infrastructure development and seismicity. We also incorporated our field observations on the commissioned Tehri dam constructed two decades ago on the Bhagirathi river. Here we briefly discuss each of the above factors and their implications followed by a detailed discussion on the Pancheswar high dam.

S. P. Sati is in the Department of Environment Science, VCSG University of Horticulture and Forestry, Bharsar, Uttarakhand 246 123, India; Shubhra Sharma is in the Department of Earth and Environmental Science, IISER-Mohali, Mohali 140 306, India; Naresh Rana is in the National Centre for Seismology, Ministry of Earth Sciences, Lodhi Road, New Delhi 110 003, India; Harsh Dobhal is in the School of Media and Communication Studies, Doon University, Dehradun 248 001, India; Navin Juyal is in the Physical Research Laboratory, Ahmedabad 380 009, India.
*For correspondence. (e-mail: shubhra@iisermohali.ac.in)

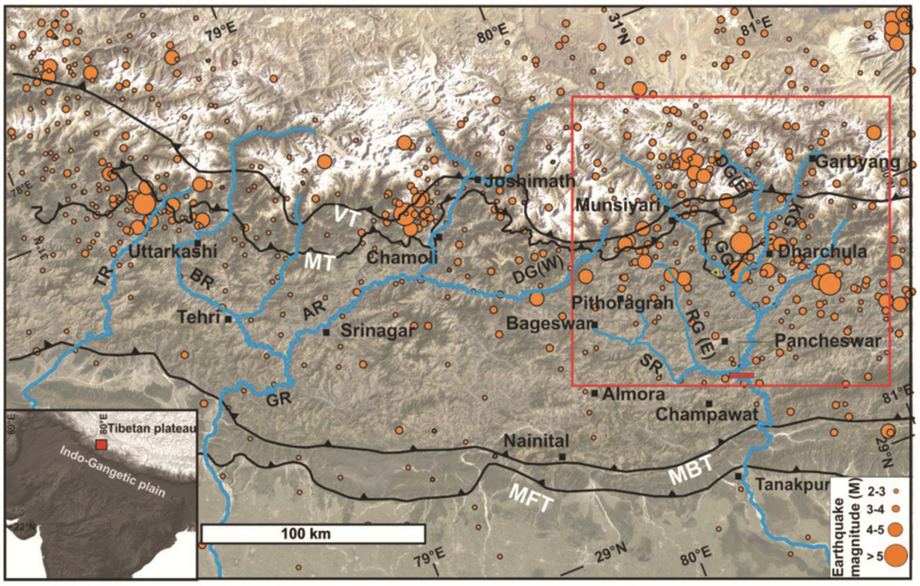

Figure 1. The main map shows the distribution of earthquake epicentres in Uttarakhand, along with major structures and the site for the proposed Pancheshwar high dam on the Kali River. The red rectangle is the catchment area of Pancheshwar hydropower project (shown in Figure 2). MBT, Main Boundary Thrust; MFT, Main Frontal Thrust; VT, Viakrita Thrust; MT, Munsiari Thrust; KG, Kaliganga; DG (E), Dhauli Ganga (East); GG, Goriganga; RG, Ramganga; SR, Saryu River.

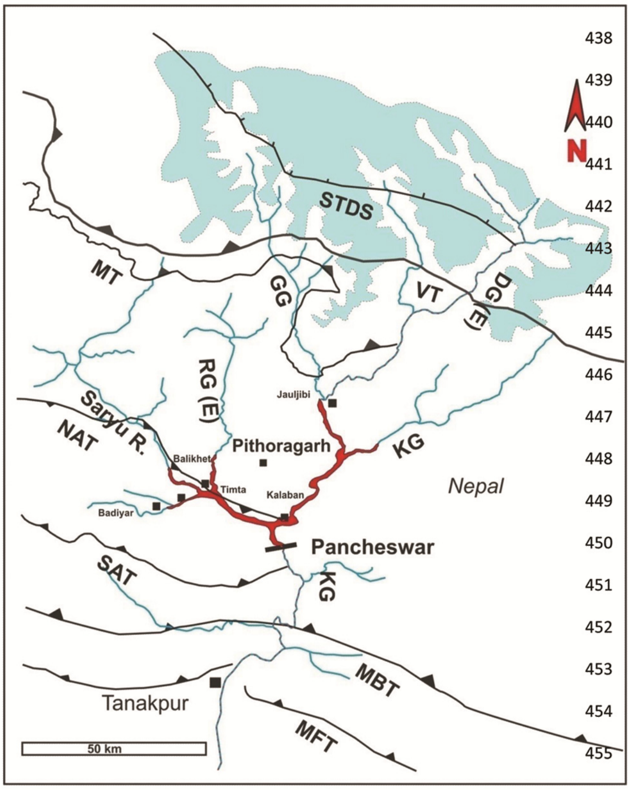

Figure 2. The catchment area of Kaliganga river basin. The rivers traverse the Trans-Himalaya, Higher Himalaya and the Lesser Himalaya. The extent of the Pancheshwar dam reservoir is shown in red colour. Note that Kaliganga, Dhualiganga east and Goriganga have upper catchment in the glaciated and paraglaciated terrain (shown in blue). STDS, South Tibetan Detachment System; VT; MT; NAT, North Almora Thrust; SAT, South Almora Thrust; MBT; MFT; KG; DG (E), GG, RG(E), Ramganga (East).

Pancheshwar dam

The 315 m high Pancheshwar dam (29.4439°N, 80.2428°E) is proposed on the Kali river bordering northern Nepal and India and is a joint venture of the two countries. The project has a drainage area of ~12,000 sq. km, out of which ~2700 sq. km lies in the glacial and paraglacial zones (Figure 2). The rock fill dam will create a reservoir of ~116 sq. km, out of which ~76 sq. km would be in India. There have been doubts regarding the impact of this project on the terrain and its ecosystem besides concerns on the disruption of the socio-economic conditions of the people living in Pithoragarh and Champawat districts of Uttarakhand[15].

Geology, structure and seismicity

The Kali river originates from the Tethyan Sedimentary Sequences (TSS) near Kalapani and traverses the South Tibetan Detachment System (STDS) near Chiyalekh. The river is joined by two major glacier fed tributaries, viz. the Dhauliganga and Goriganga[16–18]. After emerging from the glaciers, the rivers traverse through deep valleys and gorges of the Higher Himalayan Crystalline (HHC). The HHC rocks are demarcated by MCT from the low grade meta-sedimentary rocks of the Lesser Himalaya in the south. The MBT separating Siwalik rocks in the south and the Almora crystalline rocks in the north lies ~10 km downstream from the Pancheshwar dam site. The Pancheswar dam reservoir would be extending across the

North Almora Thrust (NAT), spreading over Garhwal Group of rocks consisting of dolomite, shale, quartzite, chlorite, schists and phyllite[15,19]. The NAT passes through 5 km north of the dam site whereas the South Almora Thrust (SAT) traverses ~20 km south of the dam site[15,19] (Figure 2).

During the last 100 years, earthquakes of magnitude >7.5 jolted Assam (1950), Bihar (1934) and Kangra (1905)[20]. However, Uttarakhand Himalaya is yet to face high magnitude earthquakes (>7.5) as being part of the Central Himalayan seismic gap[21]. The probability of a high magnitude earthquake in the gap areas is more, yet the precise timing of the earthquake cannot be predicted accurately[22]. It is worth mentioning that in the Nepal Himalaya most of the hydropower projects are run-of-the river type and lack any major reservoir[23] and yet majority of them were damaged during the 2015 Gorkha earthquake[24]. The project area of our study lies in zone IV of seismic zone map of India where various faults around the proposed site are suggested to be currently active and therefore highlights the increased vulnerability of the site to seismic hazard. For example, according to Pancheshwar dam pre-feasibility report[19], a potentially active Rangunkhola Fault capable of generating an earthquake of 7.4 magnitude traverses the dam site in Nepal Himalaya. Further, seismological studies indicate that the Kapkot–Dharchula and the adjoining Darchula–Bajang area in NW Nepal are frequently rocked by earthquakes of magnitude 5 to 6.5 (refs 13, 15). The northeastern part of the Kumaun Himalaya (location of Pancheshwar dam) is also tectonically active[25]. The earthquake-induced threat increases further due to proximity of the dam site to the Himalayan Frontal Thrust (HFT), where the probability of larger earthquakes is considered to be high[26]. In addition to this, the pre-feasibility study report[19] has already indicated that there are zones in the Saryu river valley which are prone to slope instability.

Reservoir-induced seismicity

There is a growing concern regarding the implications of impounding large water bodies in a tectonically active terrain like the Himalayas[27,28]. Engineers are capable of constructing *fail-safe dams* in the event of a big earthquake in tectonically active regions[29]. However, will the periphery of a *fail-safe dam* still remain safe with large water impounding and tempered slopes during the constructional activity? Various scientific studies on Tehri dam have now given us a reasonable understanding on this issue. One of the first studies[30] stated that, 'The proposed 265 m high Tehri dam in India would lie in one of the most hazardous areas in the world with respect to earthquakes. A magnitude 8 or greater earthquake may be expected under the dam. Due to the unique tectonic setting and lack of detailed studies, little is known about the expected ground motion, but indirect evidence suggests acceleration of over 1 g. In these circumstances the dam design should be subjected to the most rigorous dynamic analysis.' Another study[31] stated that, 'Tehri dam is located in close proximity of the south-dipping Tons Thrust which has experienced over 20 earthquakes (M 1.6–2.8) in 20 km radius of the dam site after the initial filling that started in 2005 till 2008'. The studies attribute earthquakes to tectonic loading on the active Tons Thrust due to local seismicity coupled with reservoir loading and unloading which might generate earthquake(s) and cause additional seismic risk in this critically stressed region[28]. The study[28] mentions that 'reservoir impoundments for hydroelectricity generation, due to their large size and associated water load, may cause measurable deformation and are considered to have triggered strong earthquakes'. Further, GPS and satellite (InSAR) based data indicated that the area around Tehri dam was undergoing deformation for which annual filling and emptying of the Tehri reservoir was implicated[28]. Considering the structural configuration and modern seismicity (Figure 1) it appears that the Kaliganga watershed is more susceptible towards reservoir-induced terrain instability compared to Tehri (Bhagirathi valley).

High sediment availability

The Himalayan rivers contribute ~10% of the total global sediment budget[32] where ~44% of total sediments are stored in the glacially scoured valleys[33]. It has been suggested that the upper catchment of the major river valleys in the Himalaya are not sediment limited, instead they are transport limited[34]. During the extreme precipitation events triggered by a combination of Indian Summer Monsoon (ISM) and mid-latitude westerlies[10,35,36], the sediments from the upper catchment (paraglacial areas) are mobilized downstream which clog the river courses as observed during June 2013 Kedarnath tragedy[8,34]. During the Pareechu landslide flood outburst in 2005, ~41% of the total annual suspended sediments of Satluj river was contributed by this single flood event of the tributary called Pareechu river[37]. The estimated buffering time of sediments in the Trans-Himalayan river catchment (north of MCT) is over 10^3–10^4 years[38]. Given the long sediment residence time in this region, the terrain is a sediment filled hotspot awaiting a favourable trigger for sediment mobilization as observed during August 2010 Leh disaster[39] and the June 2013 flash flood in the Mandakini river valley[34]. Considering that the extreme hydrological events are likely to increase in future due to the increase in global temperature[40,41], it is important to study in detail the dynamics of the glacial fed Himalayan rivers for their carrying capacity (both in terms of water discharge and sediment load) and the changes in the stream profile gradient that may occur due to high sediment flux and may adversely impact the projected benefits from the proposed hydropower projects.

The Himalayan rivers constitute a combined flow of sediment, water and energy[42]. Therefore, it is important to integrate the knowledge of sediment dynamics with the hydrological flow for the sustainability of engineering structures (dams). The upper catchment of the Kali river lies in paraglacial zone and is presently conditioned by indirect influence of the valley glaciers[43]. Large amount of sediment is generated due to freezing and thawing of seasonal snow and eroding glaciers which descend down to an elevation of ~3000 m. The glacial-fed river valleys, Kaliganga (above Garbayang village), Dhauliganga east (around Sipu village), Darma and Goriganga (above Rilkot village) are clogged with moraines, talus cones and debris flow deposits[16,44–46] (Figure 3). Extreme precipitation events triggered by both ISM and westerlies[35,36] mobilize these paraglacial sediments and also destabilize slopes to trigger debris flow/landslides particularly from sparsely vegetated Higher and Trans-Himalaya (e.g. Kedarnath disaster, June 2013). These sediments at times temporarily obstruct river valleys to create landslide dammed lakes (Figure 4), which subsequently breach resulting in massive debris-loaded flash floods. The frequency of extreme precipitation events in Himalaya is showing an increasing trend[4] and plays an important role in the overall sediment transport[35]. Flash flood of June 2013 is the most recent example of such an event that led to large-scale sediment mobilization and aggradation in the lower valleys[34,47].

The Pancheshwar dam pre-feasibility report[19] suggests a sedimentation rate of ~2.36 mm/year with an addition of 20% bed-load, implying that the reservoir life to be >250 years. This is a conservative estimate as the bed-load in some rivers of the western central Nepal exceeds 500% to 1000% of the suspended load[48] particularly during extreme precipitation events. Valdiya[13] suggested that the sediment infilling in the reservoirs created behind dams takes place at a rate of 1.5–3 times more than anticipated. Here it is pertinent to mention that the Dauliganga dam (above Dharchula town) with 6.2 million cubic meters capacity[49] was filled with ~45% debris during the June 2013 precipitation event[47]. This would translate into ~2.8 million cubic meters of debris deposited just in a one-day flood event. Therefore, it is only logical to argue that the proposed Pancheshwar project must be reviewed incorporating these pertinent observations and execution must be planned with utmost caution.

Reservoir drawdown effect

The dam reservoir water levels fluctuate widely due to operational reasons, known as the reservoir drawdown effect (RDE), which affects stability of the surrounding slopes differentially with spatial and temporal variability in the extent of submergence/emergence. Figure 5 shows laminated sediments indicating the rhythmic fluctuations caused due to RDE at the Tehri dam reservoir. Majority of the slope failures around the reservoir rim and upstream slopes are suggested to occur due to RDE[50,51], although consensus varies on the extent of the effect (elevation) from the reservoir level. Our observations around Tehri dam reservoir suggest that this is one of the major geomorphic threats to the terrain stability in the Himalaya. Particularly, the Okhala and Mohan Negi villages along the northern fringe of the Tehri reservoir are threatened by slope instability and dislocation of agricultural

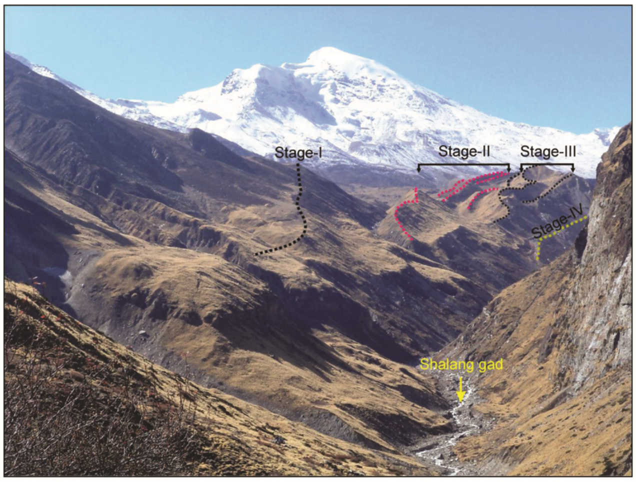

Figure 3. The oldest stage-I glacier advance in the Shalang glacier was extended down to ~15 km at an altitude of 3000 m near Rilkot in Goriganga valley[18]. Presently the upper catchments of Shalang valleys are plugged with enormous amount of glacial sediments. Glaciers expanded and contracted with varying magnitude in Uttrakhand Himalaya[17]. For example, in the Kaliganga valley, around 60 thousand years ago glacier extended down to an altitude of 3100 m (ref. 16).

Figure 4. Extreme precipitation events may lead to slope instability that can be seen in the Goriganga river which was obstructed by a landslide in 2005 (black dashed arrows) near Rilkot. Breaching of such temporary lakes sends enormous quantity of sediments downstream that can jeopardize the sedimentation rate calculations for hydropower projects.

fields (Figure 6 *a*). At Okhala village, the terraced agricultural fields located ~400 m above the reservoir level were fissured and at places were differentially dislocated. The morphology of the dislocation mimics a fault scarp with height ranging from few centimeters to tens of centimeters (Figure 6 *b*). This happens when the colluvium-laden slopes become super-saturated during high reservoir level. As the water draws down (during low reservoir level) water starts to seep into the reservoir from the colluvium. This leads to the destabilization of the repose angle causing slope instability/land subsidence and ground fissuring. Similar observations were made around Mohan Negi village (Figure 6 *c*). Apart from this, the Tehri dam reservoir rim is riddled with innumerable fresh landslides implying that the slopes are in the process of adjusting to

Figure 5. Sedimentological expression of the reservoir level fluctuations that in turn affected the slope instability around the reservoir rim (shown in Figure 6).

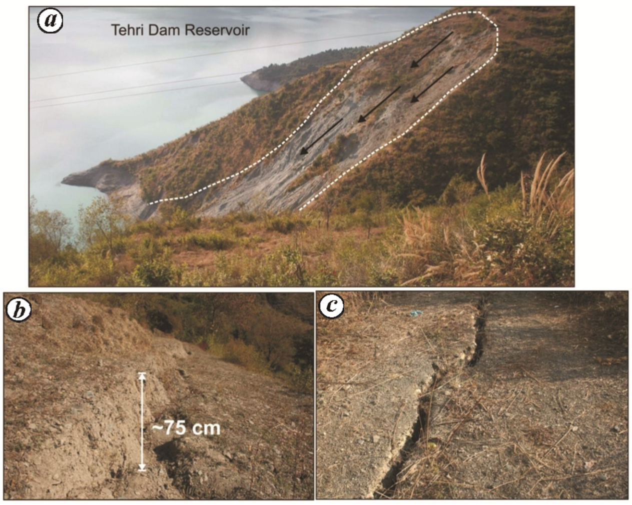

Figure 6. ***a***, Slope instability along the northern rim of Tehri reservoir around Mohan Negi village. ***b***, Vertically dislocated agricultural field above the Tehri dam reservoir caused due to frequent changes in the reservoir level. ***c***, Fissured roads can be seen above the reservoir rim around Mohan Negi village.

new hydro-meteorological conditions. Will that be ever achieved in a tectonically active terrain? With the changing inflow and outflow condition, the reservoir levels are going to fluctuate unpredictably. When the terrain stability around the Tehri dam could not be protected, how to ensure that this would not happen in a much bigger reservoir of Pancheshwar dam? In the pre-feasibility study, besides the geological aspects, there should have been detailed deliberations on the status of the valley slopes along all the four river valleys that are going to be inundated. This is critically significant for the safety, security and ecological and economic sustainability of the people who are technically not displaced but bear the brunt of the project because they live at higher elevation and are rarely compensated for the collateral damage as observed in many villages of the Tehri high dam. Therefore, it is pertinent to have a detailed geomorphic status of the valley slopes that are going to submerge. This should include extensive mapping of the slopes with emphasis on the lithology, thickness and the extent of debris/colluvium in the proposed reservoir rim area of the Pancheshwar dam. Such a study would help the dam authority to initiate slope treatment measures well in advance to avoid any collateral damage after the filling of the reservoir, and thus a situation like Tehri dam can be averted.

Finally, we are yet to develop a reasonable understanding of the behaviour of the Himalayan cryosphere in response to climate variability and changing precipitation trends. This calls for a complete re-evaluation of the methodology employed for assessing hydropower potentials of the glacial and snow fed Himalayan rivers. This is important considering the fact that majority of the hydropower projects are planned in higher Himalaya, implying that these would be sustaining largely on the melt water discharge with subordinate contribution from ISM (as the contribution of ISM decreases northward of MCT).

This is also true for Pancheshwar dam project. Recent study from HKH indicates that majority of the glaciers have retreated and lost ice mass since the mid-19th century[52]. As a consequence, the melt water contribution into rivers would be adversely impacted, which if, not accounted for, will lead to under-performance of the hydropower project. Also, it is feared that such projects are likely to impact the aquatic biodiversity in the downstream of barrages/dams due to reduced environmental flow.

Summary

We have assessed the likely environmental consequences of the proposed Pancheshwar high dam in Uttarakhand Himalaya (Indian Central Himalaya) in the light of current geologic and geomorphic understanding. The study suggests that if executed in its current format, the proposed dam raises concern about safety and its sustainability due to seismicity, reservoir-induced seismicity, slope instability due to reservoir draw down effect, and unpredictable large volume sediment mobilization from paraglacial zones. The study therefore, highlights the pressing need to re-assess the feasibility and its geo-environmental implications through multidisciplinary studies.

1. Yin, A., Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation. *Earth Sci. Rev.*, 2006, **76**(1–2), 1–131.
2. Ravi Chopra Committee, Assessment of Environmental Degradation and Impact of Hydroelectric projects during the June 2013 Disaster in Uttarakhand Part I – Main Report. Submitted to The Ministry of Environment and Forests Government of India, 2014, p. 234.
3. Grumbine, R., Edward and Pandit Maharaj, K., Threats from India's Himalaya Dams. *Science*, 2013, **339**, 36–37.
4. Strahorn, E., The tentative first steps in the creation of a Himalayan hydroelectricity market between Bangladesh, Bhutan, India, and Nepal. In *New Approaches to Building Markets in Asia*, Working paper no. 21, Centre on Asia and Globalisation, Lee Kuan Yew School of Public Policy, National University of Singapore, 2011.
5. Mayor, B., Rodríguez-Muñoz, I., Villarroya, F., Montero, E. and López-Gunn, E., The role of large and small scale hydropower for energy and water security in the Spanish Duero Basin. *Sustainability*, 2017, **9**, 1–21; doi:10.3390/su9101807.
6. Bilham, R., Larson, K., Freymueller, J. and Members, P. I., GPS measurement of presentday convergence across the Nepal Himalaya. *Nature*, 1997, **386**, 61–64.
7. Hurtado, J. M., Hodges, K. V. and Whipple, K. X., Neotectonics of the Thakkhola graben and implications for recent activity on the South Tibetan fault system in the central Nepal Himalaya. *GSA Bull.*, 2001, **113**(2), 222–240.
8. Wasson, R. J. *et al.*, The mountain-lowland debate: deforestation and sediment transport in the upper Ganga catchment. *J. Environ. Manage.*, 2008, **88**, 53–61.
9. Wasson, R. J., Sundriyal, Y. P., Chaudhary, S., Jaiswal, M. K., Morthekai, P., Sati, S. P. and Juyal, N., A 1000-year history of large floods in the Upper Ganga catchment, central Himalaya, India. *Quaternary Sci. Rev.*, 2013, **77**, 156–166.
10. Sharma, S., Shukla, A. D., Bartarya, S. K., Marh, B. S. and Juyal, N., The Holocene floods and their affinity to climatic variability in the western Himalaya, India. *Geomorphology*, 2017, **290**, 317–334.
11. Srivastava, P. *et al.*, Paleofloods records in Himalaya. *Geomorphology*, 2017, **284**, 17–30.
12. Sharma, V., 500 dams in India over 50 years old. *The Tribune*, 2011; http://www.tribuneindia.com/2011/20111205/main7.htm (last accessed on 3 January 2017).
13. Valdiya, K. S., Damming rivers in the tectonically resurgent Uttarakhand Himalaya. *Curr. Sci*., 2014, **106**, 1–13.
14. Agoramoorthy, G., The future of India's obsolete dams: time to review their safety and structural integrity. *Futures*, 2015, **67**, 22–25.
15. Valdiya, K. S., High dams in Central Himalaya in context of active faults, seismicity and societal problems. *J. Geol. Soc. India*, 2014, **49**, 479–494.
16. Juyal, N., Pant, R. K., Basavaiah, N., Yadava, M. G., Saini, N. K. and Singhvi, A. K., Climate and seismicity in the Higher Central Himalaya during the last 20 ka: evidences from Garbayang basin, Uttranchal, India. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 2004, **213**, 315–330.
17. Ali, S. N. and Juyal, N., Chronology of late quaternary glaciations in Indian Himalaya: a critical review. *J. Geol. Soc. India*, 2013, **82**(6), 628–638.
18. Ali, S. N., Bishwas, R. H., Shukla, A. D. and Juyal, N., Chronology and climatic implications of Late Quaternary glaciations in the Goriganga valley, central Himalaya, India. *Quaternary Sci. Rev.*, 2013, **73**, 59–76.
19. Pancheshwar Multipurpose Project Pre-feasibility Report. Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India, 2015, p. 151.
20. Ambraseys, N. and Jackson, D., A note on early earthquakes in northern India and southern Tibet. *Curr. Sci.*, 2003, **84**, 570–582.
21. Khattri, K. N., Great earthquakes, seismicity gaps and potential for earthquake disaster along the Himalaya plate boundary. *Tectonophysics*, 1987, **138**(1), 79–92.
22. Bilham, R., Earthquakes in India and the Himalaya: tectonics, geodesy and history. *Ann. Geophys.*, 2004, **47**, 2–3.
23. Sharma, R. H. and Awal, R., Hydropower development in Nepal. *Renew. Sust. Energ. Rev.*, 2013, **21**, 684–693.
24. Huang, Y. and Liu, J. L., Seismic performance of hydropower plant and highway system during the 2015 Gorkha earthquake in Nepal. In Proceedings of the 16th World Conference on Earthquake Engineering, 2017, pp. 9–13.
25. Pathak, V., Pant, C. C. and Darmwal, G. S., Geomorphological features of active tectonics and ongoing seismicity of northeastern Kumaun Himalaya, Uttarakhand, India. *J. Earth Syst. Sci.*, 2015, **124**, 1143–1157.
26. Wesnousky, S. G., Senthil, K., Reno, M. R. and Thakur, V. C., Uplift and convergence along the Himalayan Frontal Thrust of India. *Tectonics*, 1999, **18**, 967–976.
27. Gupta, H. K., A review of recent studies of triggered earthquakes by artificial water reservoirs with special emphasis on earthquakes in Koyna, India. *Earth Sci. Rev.*, 2002, **58**(3), 279–310.
28. Gahalaut, V. K. *et al.*, InSAR and GPS measurements of crustal deformation due to seasonal loading of Tehri reservoir in Garhwal Himalaya, India. *Geophys. J. Int*., 2017, **209**, 425–433; doi:10.1093/gji/ggx015.
29. Jatana, B. L., Fail safe large dams in earthquake prone Himalayan region. *J. Earthquake Technol.*, 1999, **387**(36), 1–13.
30. Brune, J. N., The seismic hazard in Tehri dam. *Tectonophysics*, 1993, **218**, 281–286.
31. Gupta, S., Mahesh, P., Sivaram, K. and Rai, S. S., Active fault beneath the Tehri dam, Garhwal Himalaya – seismological evidence. *Curr. Sci.*, 2012, **103**, 1343–1347.
32. Milliman, J. D. and Syvitski, J. P. M., Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *J. Geol*., 1992, **100**, 525–544.
33. Blöthe, J. H. and Korup, O., Millennial lag times in the Himalayan sediment routing system. *Earth Planet. Sci. Lett.*, 2013, **382**, 38–46.
34. Sundriyal, Y. P. *et al.*, Terrain response to the extreme rainfall event of June 2013: evidence from the Alaknanda and Mandakini River Valleys, Garhwal Himalaya, India. *Episodes*, 2015, **38**, 179–188.
35. Bookhagen, B., Thiede, R. C. and Strecker, M. R., Abnormal monsoon years and their control on erosion and sediment flux in the high, arid northwest Himalaya. *Earth Planet. Sci. Lett*., 2005, **231**, 131–146.
36. Vellore, R. K. *et al.*, Monsoon-extratropical circulation interactions in Himalayan extreme rainfall. *Climate Dynam.*, 2016, **46**(11–12), 3517–3546.
37. Wulf, H., Bookhagen, B. and Scherler, D., Climatic and geologic controls on suspended sediment flux in the Sutlej River Valley, western Himalaya. *Hydrol. Earth Syst. Sci. Discuss.*, 2012, **9**(1), 541–595.

38. Jonell, T. N., Carter, A., Böning, P., Pahnke, K. and Clift, P. D., Climatic and glacial impact on erosion patterns and sediment provenance in the Himalayan rain shadow, Zanskar River, NW India. *GSA Bull.*, 2017, **129**(7–8), 820–836.
39. Juyal, N., Cloud burst-triggered debris flows around Leh. *Curr. Sci.*, 2010, **99**(9), 1166–1167.
40. IPCC, In *Climate Change 2014: The Scientific Basis* (ed. Solomon, S.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, 2014.
41. Roxy, M. K. *et al.*, A threefold rise in widespread extreme rain events over central India. *Nat. Commun.*, 2017, **8**(1), 708.
42. Bandyopadhyay, J. and Ghosh, N., Holistic engineering and hydro-diplomacy in the Ganges–Brahmaputra–Meghna basin. *Econ. Polit. Wkly*, 2009, 50–60.
43. Barnard, P. L., Owen, L. W. and Finkel, R. C., Style and timing of glacial and paraglacial sedimentation in monsoon-influenced high Himalayan environment, the upper Bhagirathi Valley, Garhwal Himalaya. *Sediment. Geol.*, 2004, **165**, 199–221.
44. Pant, R. K., Juyal, N., Basavaiah, N. and Singhvi, A. K., Late Quaternary glaciation and seismicity in the Higher Central Himalaya: evidence from Shalang basin (Goriganga), Uttranchal. *Curr. Sci.*, 2006, **90**, 1500–1505.
45. Ali, S. A., Aadhar, S., Shah, H. L. and Mishra, V., Projected increase in hydropower production in India under climate change. *Sci. Rep.*, 2018, **8**(1), 1–21.
46. Bisht, P., Ali, N. S., Shukla, A. D., Singh, S., Sundriyal, Y. P. and Juyal, N., Chronology of late Quaternary glaciation and landform evolution in the upper Dhauliganga valley (Trans Himalaya), Uttarakhand, India. *Quaternary Sci. Rev.*, 2015, **129**, 147–162.
47. Theophilus, E., A river pulse. A discussion paper on the flood event in June 2013, Mahakali basin, Uttrakhand, Himal Prakriti – A trust for nature, 2013, pp. 1−25; http://www.himalprakriti.org/
48. Carson, B., Erosion and sedimentation processes in the Nepalese Himalaya. ICIMOD Occasional Paper No. 1. Kathmandu, 1985, p. 39.
49. Paudel, P., Regmee, S. B. and Upadhyay, S. N., Overview of June 2013 flood and landslides with focus on Dharchula disaster. *Hydro Nepal*, 2013, **13**, 57–63.
50. Sherard, J. L., Woodward, R. J., Gizienski, S. F. and Clevenger, W. A., *Earth and Earth-Rock Dams*, John Wiley, New York, 1963.
51. ICOLD, Deterioration of dams and reservoirs. Examples and their analysis, ICOLD, Paris, Balkema, Rotterdam, 1980.
52. Bolch, T. *et al.*, The state and fate of Himalayan glaciers. *Science*, 2012, **336**, 310–314.

ACKNOWLEDGEMENTS. The views expressed here are of the authors, and do not necessarily reflect the views of their respective institutes. Authors thank the two anonymous reviewers for their useful suggestions and comments. We also thank Sekhar Da, Sushil Bahuguna and Pahar team for the support and help.

Received 18 April 2018; revised accepted 6 February 2019

doi: 10.18520/cs/v116/i9/1483-1489